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UNDERWATER NOISE AND THE CONSERVATION OF DIVERS' HEARING: A REVIEW

Volume I

Prepared as a Cooperative Effort

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EXECUTIVE SUMMARY

This report presents the results of a review of research conducted on underwater hearing as related to noise hazards to divers and to the conservation of their hearing. Because of the large scope of the problem, this volume of the report concentrates on air-supplied bare-headed or hooded diving to depths up to 100 ft such as would be employed in ship husbandry work. It is hoped that a future volume or volumes can deal with helmet diving, greater depths, gas mixtures other than air, as well as expanding on certain of the materials already discussed herein by presenting the results of additional experimental work and analysis.

Working divers are frequently subjected to high levels of underwater acoustical noise that may be hazardous to hearing. Explosive events can instantaneously do physical damage to the hearing mechanisms. In a more subtle way, long-term exposure to loud noises (either continuous or impulsive), produced for example by underwater tools, can eventually result in hearing losses just as unprotected factory workers have experienced hearing degradation by many years of exposure to high noise levels. This type of permanent noise-induced hearing loss is caused by *repeatedly stressing the sensory cells* (hair cells) of the inner ear which initially results in their dysfunction but ultimately in their destruction. In order to better understand the effects on human hearing of exposure to high levels of noise, knowledge of the structure and functioning of the ear is helpful. Therefore, some tutorial information on the ear has been provided in Section 2 of the report.

One of the problems encountered when conducting the review of research on underwater hearing is that different investigators have used different sound level reference values when presenting their results. Again for tutorial purposes, a discussion of the various references is presented in Section 3 of the report. A sound pressure reference value of 20 micropascals appears to be most commonly used today for those involved in hearing research or noise control work, both for air and water environments. Throughout this report we have also tried to consistently use 20 μPa as the sound pressure level reference. Table 3-1 provides the information necessary to convert sound levels using various references to sound levels re 20 μPa .

A large number of in-water experiments have been performed in the past for the purpose of establishing the relationship between the thresholds of audibility under water and in air. In general, underwater thresholds have been obtained by having divers listen for minimum levels of sound (e.g., tones) coming from an underwater projector. In contrast to these underwater "sound field" measurements, in-air hearing thresholds (if measured) have generally been obtained using standard pure-tone audiometric techniques involving a sound-proof booth and an audiometer with a factory-matched earphone. Some investigators have merely compared their in-water data to standard threshold curves representing *normal young ears* (without audiometric measurements), yet their subjects may not have had *normal* hearing. In the absence of *in-air* sound field measurements, audiometric data need to be converted to equivalent free-field values so that they can be compared with the underwater threshold measurements and thus establish the differences between hearing in the two media. Evidence suggests that, in general, the required audiometric transformations have not been properly made. Confusion has existed in the interpretation of such terms as minimum audible field (MAF), minimum audible pressure at the observer's eardrum (MAP), and minimum audible pressure as measured using a standard coupler (MAPC). In Section 4, we have attempted to provide a clarification of these terms and have given examples of how audiometric data can be converted to equivalent free-field data. It has also been noted in Section 4 that a change in U.S. audiometric standards (amounting to differences of 6 to 15 dB depending upon frequency) was taking place during the period between 1964 and 1970 and that a number of the experiments on underwater thresholds of audibility were conducted during this same period. (These audiometric standards are required as part of the transformation of audiometric data to equivalent free-field values.) Unfortunately, the investigators failed to indicate in their technical journal articles which standards were being applied, thus creating some additional uncertainty regarding their in-air results. The material presented in Section 4 is essential to the interpretation of the individual underwater threshold experiments discussed in Section 5.

At least a dozen experiments dealing with underwater thresholds of audibility have been conducted beginning with Sivian's work in 1943 and continuing with other investigators through 1975 (refer to Table 5-1). The results of these experiments have differed significantly. It has been essentially impossible to establish the actual relationship between underwater and in-air hearing with any degree of confidence because of the wide disparity in these results. If a realistic transformation between water and air could be determined, then in-air noise exposure limits could easily be applied to the underwater environment (for the bare-headed diver case). In Section 5 of this report, each of the

(known) experiments has been evaluated as to potential weaknesses or areas of uncertainty in an effort to establish their validity and to better define the air-versus-water hearing relationship. Some of the key deficiencies and problems noted have included high or unknown ambient noise levels, a lack of monitoring of the actual in-water sound field at the diver's head position, and a lack of objective information on the quality of each subject's hearing; i.e., no in-air hearing sensitivity data. On the basis of these key deficiencies, the results of certain experiments were set aside as being unreliable and the remaining *better* experiments, namely those of Hamilton (1957), Hollien *et al.* (1967, 1969-two papers, and 1975), and Smith (1965 and 1969), were further evaluated as a group. The agreement between the results obtained by these three investigators, although not perfect, was better than that obtained by considering the results of *all* experiments, including the *unreliable* ones. Using their data, an average curve representing the "best-estimate" of underwater thresholds of audibility (for young listeners with normal hearing) as a function of frequency was calculated (see Figure 5-33). Adjustments were made to the original data to account for (normalize) the different hearing sensitivities of the subjects used and, where considered appropriate, for the change in audiometric standards that occurred during the 1964-1970 time frame (ASA Z24.5-1951, changing to ISO 389-1964 or ANSI S3.6-1969). The underwater thresholds represented by this average (adjusted) curve are generally lower than those presented by most of the investigators, indicating that the actual differences between underwater and in-air hearing sensitivities may be significantly less than previously thought. Section 7 of this report provides further evidence of this possibility.

If the water-versus-air threshold differences are less than previously assumed, it may be even more important to provide protection from hearing damage when, for example, divers use noisy tools in the underwater environment. Divers' hoods will provide a certain amount of noise attenuation and should be seriously considered as protective devices. The results of four different investigations of the attenuating properties of divers' hoods based upon underwater threshold measurements are discussed in Section 6 of the report. In addition, the results of three investigations in which hydrophones were covered with hoods or hood material to measure attenuation properties are presented. Sufficient evidence exists from these two different experimental approaches to show that, for depths up to at least 30 ft, divers' hoods offer a significant amount of protection at frequencies of 1000 Hz and above, and little or no protection at frequencies of 250 Hz and below. The growth function between these two frequencies is not yet clearly defined and could depend upon factors such as hood thickness. There is some evidence to indicate that the hood attenuation values will hold for depths up to 100 ft but further

experimental work is needed to confirm this. In the interim it is proposed that hoods be considered acceptable as hearing protection devices for depths to 30 ft or slightly greater (allowing work to ship keel depths). A minimum hood thickness of 3/16-in. should probably be specified at this time based upon existing data. The hood obviously should be in good condition and should fit properly. To be conservative in estimating the effect of hood attenuation for divers using noisy underwater tools, and pending the collection of additional experimental data, we propose that only a 20 dB loss be assumed above 1 kHz, and zero loss be assumed below 1 kHz. (The beneficial effect for any given tool will depend upon its actual noise spectrum.) It is suggested that in any future hood attenuation investigations, the use of the *acoustic reflex* (at sound levels well above threshold) as an indicator of comparable sensation levels for the hood-on and hood-off conditions be considered as perhaps a better approach than threshold measurements which are easily contaminated by background noise. The acoustic reflex technique was used in an experiment, described in Section 7 of this report, which was conducted to establish the differences between in-air and underwater hearing at suprathreshold sound levels.

Because of the uncertainties associated with the measurement of underwater thresholds of audibility, and the gross lack of consistency among the threshold results obtained by the many investigators, other approaches to determining the differences between in-air and underwater hearing were considered. We conceived of two approaches for comparing in-air and underwater hearing which would be conducted at *suprathreshold* (well above threshold) sound levels. One approach involved the determination of *equal loudness levels* in air and in water, and the other involved measurements of *acoustic reflex thresholds* (ART) and acoustic reflex growth in the two media. In the equal loudness comparison approach, a swimmer is placed on his or her side in water and at the surface, with one ear (and most of the skull) under water and the other ear projecting just out of the water. The underwater ear (and skull) is stimulated with pulses of sound (tones) from an underwater transducer placed below the swimmer. The above-water ear is stimulated alternately with pulses of the same frequency from an in-air loudspeaker placed above the swimmer. One of the sound levels is raised or lowered as directed by the subject to match the other fixed sound level. Various levels and frequencies can be used, the swimmer's ear positions can be switched, the contents of the ear canal can be varied (air versus water), and a number of subjects can be used to obtain statistically significant data. The acoustic reflex comparison approach is similar except that the in-air loudspeaker is not used. The concept takes advantage of the naturally occurring *acoustic reflex*; i.e., the activation of the muscles of the middle ear when the ear is subjected to loud sounds, which serves as a protective mechanism. It is an interesting fact

that stimulation of only one ear will elicit the response in both ears. Thus, by stimulating the underwater ear of our swimmer, we can observe the reflex in the above water ear using a probe that detects impedance changes at the eardrum. If we measure the sound level for reflex activation in water and compare it to an equivalent air activation level, we have a direct comparison of in-water to in-air hearing performance at sound pressure levels well above threshold and in the region of interest (at levels where damage risk begins). Further, if we systematically increase the sound level at each frequency, we can obtain relative measures of reflex growth which may be extremely important for establishing correct trading relationships for calculating permissible exposure times. (Since underwater hearing is primarily by bone conduction, the reflex will not protect the ear, thus a knowledge of the rate of growth is potentially very important.)

A series of tests was conducted to demonstrate the feasibility of these two concepts. It is emphasized that this series did not represent a complete experiment since borrowed in-house equipment was employed, and *limited* free off-hours time was obtained at one of the University's swimming pools (on a not-to-interfere basis). Measurements were made at only 1, 2, and 4 kHz using two subjects. Only the right ear of each subject was positioned under water, data were obtained only for the condition of *air in the ear canal*, and there was no opportunity to conduct repeat measurements. In spite of these limitations, the results of the tests were significant. Specifically, the differences between in-air and underwater hearing were lower than expected based upon underwater threshold work, and this was true for both the *equal-loudness* and *acoustic reflex* tests.

Two other investigations at suprathreshold sound levels provide additional experimental evidence supporting smaller differences between underwater and in-air hearing than are commonly accepted. Montague and Strickland (1961) conducted an experiment on the ability of 23 divers to *tolerate* a high intensity underwater tone of 1500 Hz. Smith and Wojtowicz (1985) performed an experiment using 4 divers with each subject exposed to a specific frequency tone (700, 1400, or 5600 Hz); the intent was to find sound pressure levels in air and in water that would produce equivalent amounts of temporary threshold shift (TTS). The results of both of these experiments do point toward air-versus-water hearing differences that are lower than expected based upon underwater thresholds. In conclusion, the combined evidence of our work and these two other suprathreshold investigations *strongly suggest that the current underwater sound pressure level exposure limits are invalid and err on the unsafe side by significant amounts*. Figure 7-18 in this report compares the results from the *suprathreshold* experimental work with the standard U.S. Navy reference curve (promulgated as an interim guideline

in 1982 -- see Appendix A). There are large differences between the Navy curve and the suprathreshold data. The suprathreshold data are not yet sufficient to define a functional relationship between sound pressure level difference and frequency. Therefore, we are recommending as an *interim* measure that an average value of 37 dB as shown in Figure 7-18 be used as the SPL difference between underwater and in-air hearing for the establishment of *revised* underwater sound pressure level limits pending the collection of additional suprathreshold data. We also recommend that A-weighting be applied to the underwater case just as it is applied to the in-air case since A-weighting is intended to de-emphasize low and very high frequencies which are, for a given SPL, less hazardous to hearing. As indicated earlier, diving hoods should be used to help protect against noisy tools. The absence of the protective benefit of the acoustic reflex in the underwater environment (because of bone conduction) must also be taken into account when establishing underwater noise exposure limits.

Finally, Section 8 of this report proposes an underwater noise exposure standard for bare-headed (or hooded) divers breathing air in shallow water based upon the review material and experimental evidence presented in the earlier sections. It is proposed that a new set of spectral weights for use in underwater noise exposure situations be developed -- the units would be "dBU" which would be analagous to dBA (A-weighted sound levels) in air. They would incorporate A-scale weights, along with air-water sensitivity differences as illustrated in the examples presented in Table 8-2. The role of the acoustic reflex, both in air and in water, must also be considered. Slightly below the intensity range where damage risk begins, the acoustic reflex is activated, yielding a graded response which, in air, attenuates transmission of low-frequency sound to the cochlea. In water, the reflex still occurs, but is ineffective in attenuating the primarily bone-conducted sound; this factor is also taken into account in the proposed exposure standard (see Figure 8-1 and the related discussion). In summary, the proposed standard differs from the existing underwater standard by the inclusion of A-scale weighting and corrections for missing acoustic reflex attenuation in water, plus a new set of values (which may be further refined) for air-water hearing differences.

Summary of Recommendations in this Report

- Establish a new underwater noise exposure standard for air-supplied bare-headed and hooded diving:
 - It is proposed that a new set of spectral weights be generated for use in underwater noise exposure situations (dBU), analogous to A-scale weighting in air (dBA).
 - The new spectral weighting would retain the A-scale weights since they serve to de-emphasize the low and very high audio frequencies which, for a given sound pressure level (SPL), are less hazardous to hearing. (This should be as true under water as in air.)
 - The new weighting would also include corrections (air-water sensitivity differences) for the less efficient sound transmission to the human ear in the underwater environment.
 - Because the acoustic reflex is ineffective in water in attenuating the primarily bone-conducted sound, a "reflex compensation" correction is required for frequencies below about 1500 Hz. We propose that, beginning at 80 dBU, a correction would be made for which the level in dBU would increase more rapidly than the level in dB SPL. The slopes of this "reflex compensation" should be equal to $1/1-a$, where a = reflex attenuation (dB/dB). We propose that a be set at 0.5 for the octave bands centered at 125, 250, and 500 Hz, and at 0.25 for the 1000 Hz band ($a = 0$ for higher frequencies). The corresponding slopes of the dBU output function would be 2.0 and 1.33, over a 30 dB dynamic range in dBU. (Refer to Section 8.6, Table 8-2, and Figure 8-1.)
 - Exposure levels would be obtained by combining the octave-band adjusted levels in the usual manner to yield an overall level in dBU; as described in Table 8-3. The current NAVMED permissible exposure standard could then be used; i.e., 84 dB(U) for a continuous 8-hour exposure, with a 4 dB(U) trading ratio (e.g., 88 dBU for 4 hours, etc.).
- The foregoing proposals are intended to apply to continuous noise environments. For impulse or impact noise the acoustic reflex can be ignored since, except for rapid impulse trains or impulse/continuous noise mixtures, the reflex occurs too

slowly to be of any protective value in air or water. Based upon the underwater threshold and suprathreshold data presented in this report, we propose adding a number in the range of 35-40 dB to the impulse standard for air (140 dB peak level) so as to yield *at least* as protective a standard.

- Both the (better) underwater threshold data and the suprathreshold data presented in this report show that air-water hearing sensitivity differences are actually less than previously thought and may be as much as 30 dB less (at certain frequencies) than the values currently used by the U.S. Navy. A modification to the existing Navy standard definitely appears to be in order. As an *interim* measure, we propose setting the air-water hearing difference at a constant value of 37 dB over the audio frequency range. This (conservative) value is based upon the suprathreshold data presented in Section 7 and summarized in Figure 7-18. (Future experimental work may show that the sensitivity differences depend somewhat upon frequency, at which time the standard can be adjusted accordingly.)
- Sufficient experimental evidence exists to show that divers' hoods will provide a significant amount of noise protection, at least for shallow depths, at frequencies of 1000 Hz and above. It is proposed that hoods be considered acceptable as noise protection devices for depths to 30 ft or slightly greater (allowing work to ship keel depths). To be conservative, and pending the collection of additional experimental data, we propose that *only* a 20 dB loss be assumed at 1000 Hz and above and zero loss be assumed below 1 kHz. One or more "standard" hoods could be approved for Navy use. The hood should fit well and be in good condition. The hood should provide maximum coverage of the head, and a face mask that minimizes facial exposure should also be used. A minimum hood thickness of 3/16-in. should probably be specified at this time based upon existing data.
- An underwater sound level meter should be developed to serve the same purpose in the underwater working environments that existing sound level meters serve for in-air environments. The meter would independently treat octave bands of noise. For low intensities in each band, output would rise linearly (slope = 1 dB/dB) with input, after correcting for air-water audibility differences and A-weighting. Above reflex threshold, input-output curves would rise more steeply (for low frequencies), compensating for the reflex attenuation which is missing underwater. In addition to measuring octave band levels, the instrument

would provide an *overall* sound level output in dBU. The requirement for an underwater noise dosimeter should also be considered.

- Additional research is required to strengthen the data base related to the differences between underwater and in-air hearing. We propose that more experimental work at *suprathreshold* sound levels be performed to establish actual air-water sensitivity differences. The equal loudness comparisons and acoustic reflex comparisons (air versus water) described in Section 7 of this report should be extended to include more frequencies in the audio range, use more subjects, test both ears of each subject, use octave band noises as well as tones, etc.. Additional experimental work could also be performed using sound levels that produce equal amounts of temporary threshold shift (TTS) in air and in water (refer to Section 7.6.2.2 for a discussion of such work).
- The acoustic reflex and equal loudness comparison approaches should be used to more fully study acoustic reflexes in the underwater environment. The information obtained from such work would corroborate our proposed standards approach and permit a more valid estimate of the slopes of the "reflex compensation" parts of the dBU input-output functions.
- The acoustic reflex and equal loudness comparisons can also be performed *with* and *without* diving hoods (of various thicknesses) so as to obtain additional data on hood attenuation properties at shallow depths. Such tests can also be performed with and without a foam neoprene diving suit to see if there exists any measurable internal sound transmission from the body to the skull when the torso is uncovered. The behavior of diving hoods (relative to their attenuation properties), *as a function of depth*, needs to be investigated further. As suggested in Section 6.4, it might be sufficient to use the covered hydrophone approach which would not require the use of human subjects. A transmitter and receiving hydrophone could be mounted on simple rigid framework and lowered to various depths in an open body of water. The hydrophone would be covered with the diver's hood. Various thicknesses would be tested over the audio frequency range. Sound levels well above ambient noise would be used.

- Of the many investigations conducted in the past to measure the differences between underwater and in-air hearing at thresholds of audibility, only those of Hamilton (1957), Hollien *et al.* (1967, 1969--two papers, and 1975), and Smith (1965 and 1969) were judged to be reasonably thorough based upon experimental approach and conduct, and completeness of reporting. In our analysis of their results, adjustments were made to the in-air data to account for the change in audiometric standards that occurred during the 1964-1970 time frame (the authors did not indicate which standards were being used). We are fairly confident that the application of these corrections were proper for Hamilton's data (his work was performed well before 1964) and for Smith's data (clues were provided in his 1965 paper as to which standards were being applied--see page 5-59). However, we are not as confident that the adjustments were appropriate for Hollien's results. If Hollien's data did *not* require adjustment, our conclusions still would not change since his original results (i.e., his air-versus-water differences) still support the need to modify (lower) the existing Navy standards for air-water sensitivity differences. In order to clarify these issues, we recommend that copies of this report be provided to both Hollien and Smith with the hope that they will comment on the questionable areas. (There is a subtle point that should be made here. Since Hollien's data were used to set the Navy standards, why do those standards now need to be lowered? The answer is that Hollien's underwater *thresholds* were used to set the standards and not his air-versus-water *differences*. Since his subjects had poorer than "normal" in-air hearing, his underwater thresholds also were elevated above "normal".)
- Because of the uncertainties associated with the problem of underwater hearing and protection from noise, the Navy would probably be wise to enroll all noise-exposed divers in a hearing conservation program and begin to collect systematic epidemiologic data linking noise induced permanent threshold shift (NIPTS) to various noise exposure levels and types. The elements of such a program would have to be defined specifically for the *diving* population.
- It is recommended that the current review be continued and that a second volume to this report be prepared which will cover additional topics such as helmet diving, gas mixtures other than air, greater depths, noise spectra of underwater tools, and examples of permissible exposure times under the proposed standards when using the specific underwater tools (with and without diving hoods). Some

review work, although not yet complete, has already been done in these areas. The results of the proposed additional suprathreshold experimental work could also be presented in a Volume II.

1. INTRODUCTION

Working divers including commercial, scientific, and military are frequently subjected to underwater acoustical noise that may be hazardous to hearing. Typical noise sources include ship-mounted and portable sonar equipments, various explosive devices such as shark protection bang sticks and diver recall devices, tracking system "pingers", and numerous underwater tools such as impact wrenches, pneumatic rock drills, high-pressure water jet cleaners, and gunpowder actuated stud guns. In addition to waterborne sound, divers may encounter high noise levels in dry hyperbaric environments, such as when wearing diving helmets or in hyperbaric chambers, due to high rates of supply gas flow.

With certain sound intensity levels and durations of exposure, temporary hearing loss may occur. Higher exposure levels or longer durations of exposure may result in permanent hearing loss, which can be incurred in a relatively short period of time. Permanent hearing loss can also result from the more insidious effect of years of exposure to "noisy" environments. There have been numerous epidemiological surveys of groups such as factory workers which demonstrate this latter effect for the in-air situation. Exposure to intense noise can produce other effects associated with the ear such as tinnitus ("ringing" in the ear) and disturbances of the vestibular system causing loss of balance or dizziness.

Permissible limits for occupational noise exposure have been established for the in-air community by the Occupational Safety and Health Administration (OSHA) of the Department of Labor. Although work done in laboratories with both human subjects and animals has contributed significantly to a better understanding of the problems associated with noise induced hearing loss, the noise exposure limits have been based primarily upon the results of various epidemiological studies, and they reflect a reasonable compromise between scientific, social, economic, and political factors. It is noted that the specified exposure limits are reasonably well accepted by the scientific community for the case of continuous noise working environments, although some would argue that they are still not conservative enough. However, for the impulse noise case, many more questions and uncertainties exist, and we can expect that the guidelines and specified exposure limits for impulse noise may be modified in the future as more research is done in this area.

The specified in-air standards are not directly applicable or transferable to the in-water environment, or even to certain dry hyperbaric situations, since the ear performs differently in water or under high gas pressures than it does in normal air. Further, epidemiological data based upon larger diver populations and taken under controlled (or known) noise conditions do not exist. Those experiments that have been performed using divers always involve relatively small samples, and the numbers of experiments are relatively few. OSHA has not yet considered the underwater or dry hyperbaric problems, but there have been attempts by other agencies such as the U. S. Navy to provide some interim guidance in these areas. However, because of the limited and sometimes conflicting information used in establishing the guidelines, some degree of uncertainty exists as to their validity. Are the selected exposure limits overly conservative or too lax?

In addition to the problem of establishing realistic and practical noise limits and exposure times for both wet and dry hyperbaric situations, the diving community is faced with the problem of being able to accurately measure the noise levels in the various working environments so that the criteria can be applied properly. When noise levels are excessive, methods or devices for protecting the divers' hearing to allow extending working times also need to be developed.

In this report we present the results of a review of available research literature dealing with the problem of noise hazards to divers and attempt to identify and clarify the major issues involved. We concentrate in the current study on the field of shallow-water air supply diving as employed, for example, in ship husbandry work. For the benefit of certain readers, some tutorial information concerning the structure and functioning of the ear is provided.

2. A BRIEF REVIEW OF THE ANATOMY AND FUNCTIONING OF THE EAR

2.1 Introduction

In order to better understand the effects on human hearing of exposure to high levels of noise, either in air or under water, some knowledge of the structure and functioning of the ear is helpful. The hearing mechanisms can be structurally damaged by high-level short-term acoustic events such as explosions or emission of high-energy sonar pulses when these occur at close range. Explosive events can rupture the eardrum, and/or damage the ossicular chain (the three small bones in the middle ear). The inner ear, particularly the auditory sensory cells (hair cells) in the cochlea, can also be permanently damaged in a relatively short period of time by extremely high levels of sound. In a more subtle way, the sensory cells of the inner ear can be slowly damaged by repeated long-term exposures to lower noise levels such as those encountered in factories or shipyards. According to Melnick (in Harris *et al.*, 1979, Chapter 9), "the primary mechanism for chronic noise damage appears to be physicochemical, metabolic stress exerted on the maximally stimulated cells. The end result is sensory cell dysfunction resulting in temporary hearing loss or sensory cell destruction creating a permanent hearing loss depending on the degree of cellular injury." In this section of the report, brief descriptions of the various components of the auditory system and their functions are provided. It is convenient, when describing the actions of the ear, to consider three "subsystems"--the *outer ear*, the *middle ear*, and the *inner ear*. Figure 2-1 is a representation of the human ear.

2.2 The Outer Ear

The *outer ear* consists of the visible external portion called the *pinna* or *auricle*, and the *ear canal* or *external auditory meatus*.

The *pinna* is an intricately shaped cartilaginous shell covered with skin. In some mammals the pinna is very movable and serves to *collect* sound from various directions. In man, this function is vestigial and he can hear almost as well without an external ear.

This section of the report was compiled by Paul C. Kirkland primarily from materials provided by Robert A. Dobie and Phillip A. Yantis.

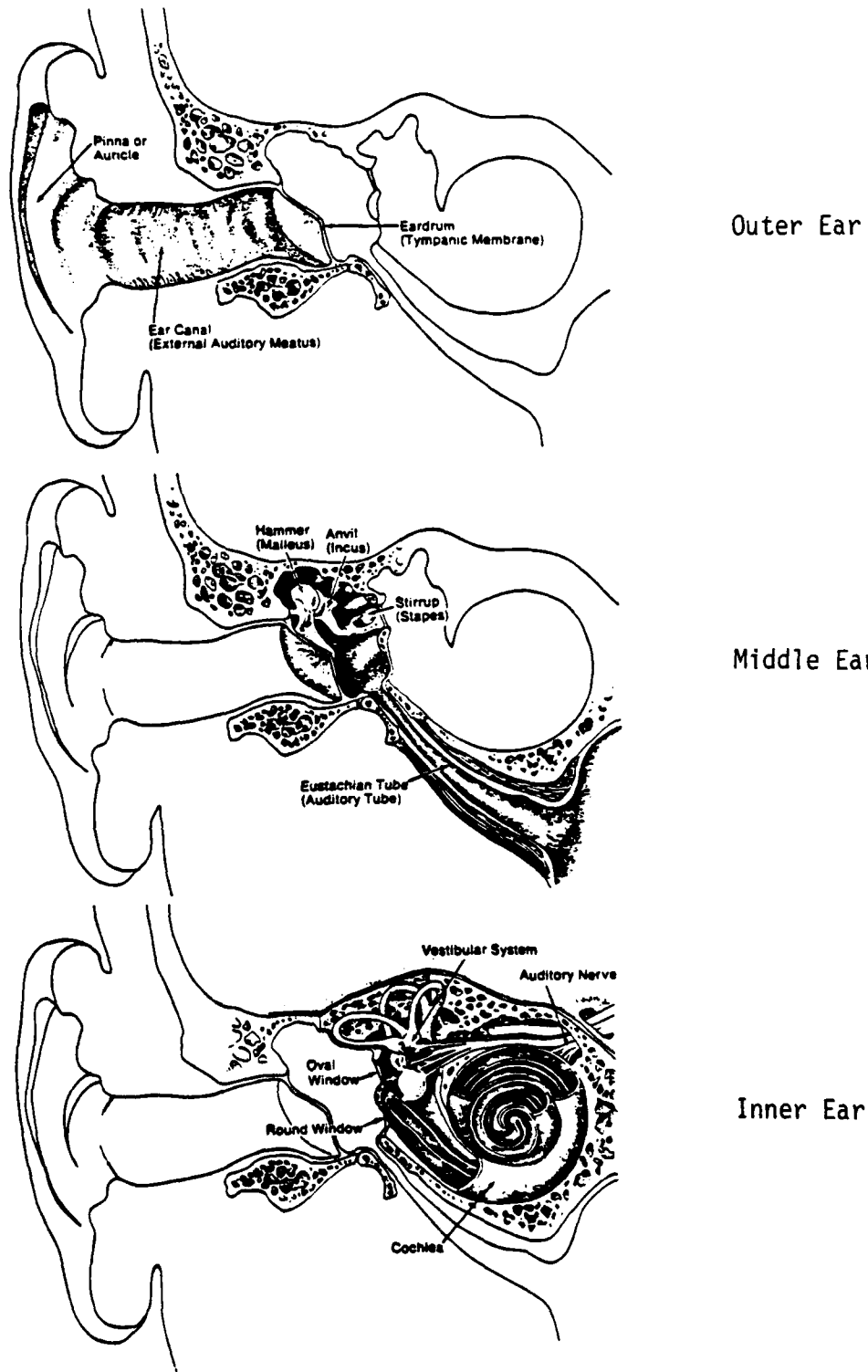


Figure 2-1

Cross section of the right temporal bone showing the components of the outer ear, middle ear, and inner ear. (Courtesy of P. A. Yantis, from Alliance of American Insurers, Chicago: Technical Guide No. 9, 1981.)

The *ear canal* is open at the external end and terminates at the inner end with the *eardrum* or *tympanic membrane*. The canal is also skin covered having a cartilaginous outer portion and bony inner portion. It is roughly tubular in form and is about an inch in length. The human ear canal, acting as a rigid tube closed at one end, has a resonant frequency of about 3 kHz and, therefore, it serves to amplify sound waves near this frequency. Figure 2-2 shows the ratio of sound pressure measured at the eardrum to the free-field (face on) sound pressure, plotted as a function of frequency. The combined effects of the head, the pinna, and the ear canal resonance on sound reaching the eardrum are included. We see that a 15 dB (or greater) increase occurs between 2 and 4 kHz, a large part of which is due to the ear canal resonance effect.

The *tympanic membrane*, which forms the boundary between the outer and middle ear, is a trilaminar structure consisting of an outer lining of skin, a fibrous middle lamina, and an inner layer of respiratory mucosa which is continuous with the lining of the middle ear. (The eardrum is sufficiently thin that structures within the middle ear can be seen when using a bright light in the ear canal.) The eardrum is set into vibration when sound enters the ear canal.

2.3 The Middle Ear

The *middle ear* is an air-filled cavity located within the temporal bone. It is connected to the back of the nasopharynx by the *eustachian tube* which allows equalization of pressure on both sides of the eardrum. A chain of three delicately suspended bones, the *ossicles*, are located between the tympanic membrane and the oval window of the cochlea. The *hammer (malleus)* is attached to the tympanic membrane, the *anvil (incus)* occupies an intermediate position, and the *stirrup (stapes)* is in direct contact with the oval window and thus with the fluid in the cochlea.

The mechanical system provided by the ossicles serves as an impedance matching transformer which converts the low-pressure/high-volume velocity excursions of sound in air to high-pressure/low-volume velocity excursions in the perilymphatic fluid of the cochlea. (If these bones were missing, most of the sound energy would be reflected rather than transmitted into the fluid of the inner ear.) The impedance matching is accomplished by ossicular lever action and by the area relationship between the eardrum and stapes footplate. As shown in Figure 2-3, the handle of the malleus is slightly longer than the long process of the incus resulting in a lever ratio of about 1.3. The effective area of the eardrum is about 17 times greater than that of the footplate. The combination

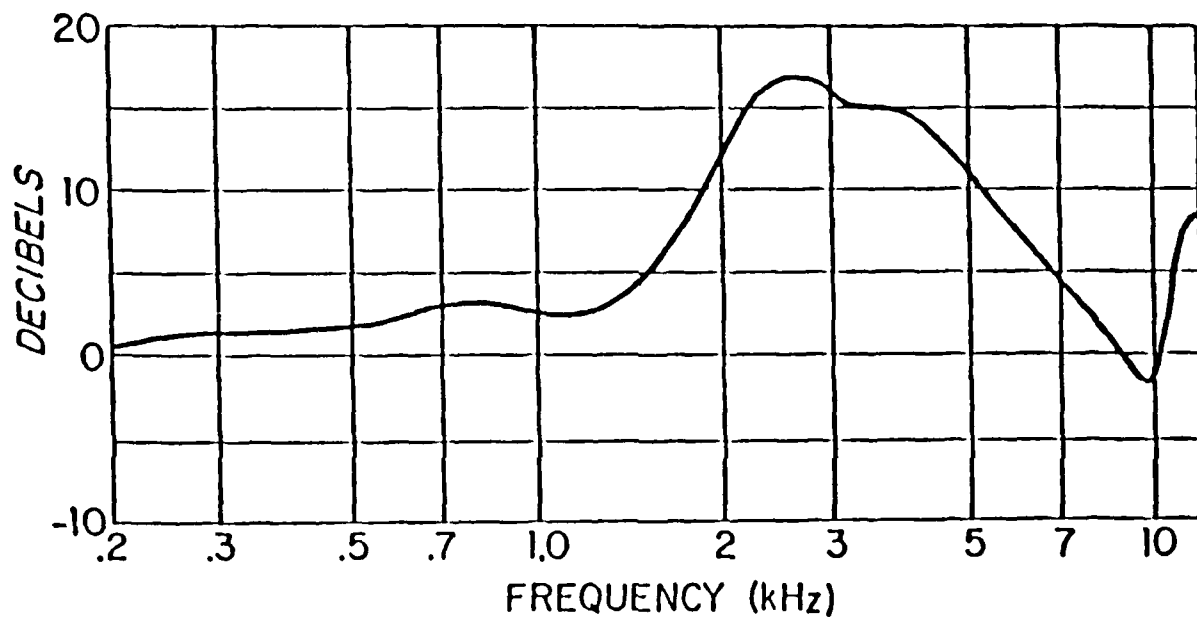


Figure 2-2

A tiny microphone placed near the tympanic membrane records different sound levels (for many frequencies), in response to a constant sound source, than a microphone placed in the same point in space, but with the person absent. This effect, due mainly to ear canal and pinna resonance, is demonstrated here; the difference between the two microphone readings is plotted as a function of frequency. (Courtesy of R. A. Dobie.)

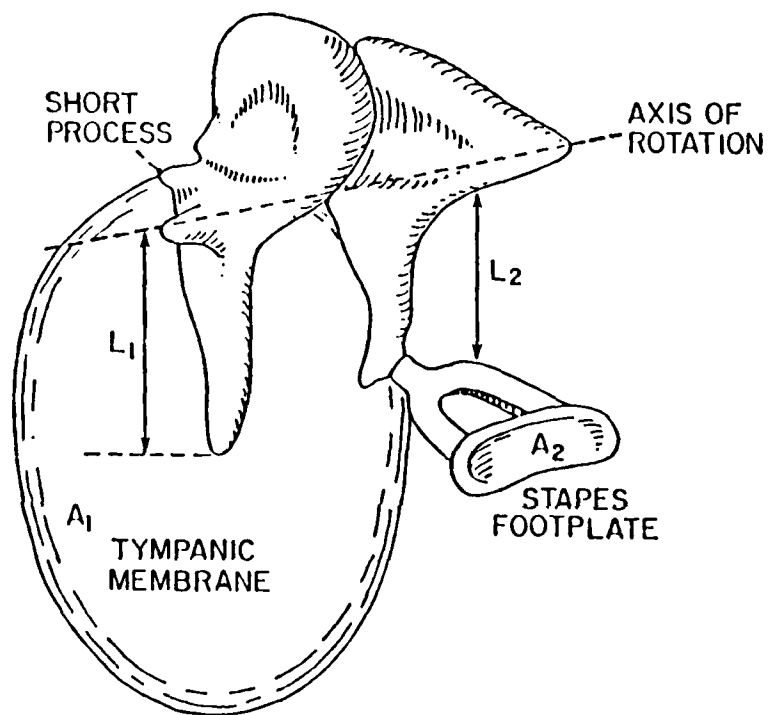


Figure 2-3

Both the difference in length between malleus handle (L_1) and incus long process (L_2), and the much larger ratio of areas of tympanic membrane (A_1) and stapes footplate (A_2) are shown here. (Courtesy of R. A. Dobie.)

of these two effects provides an approximate 22-fold (27 dB) increase in sound pressure from the eardrum to the inner ear.*

There are two muscles which can affect sound transmissions through the middle ear: the *tensor tympani* which attaches to the malleus, and the *stapedius* which attaches to the stapes. Loud sounds will cause these muscles (primarily the stapedius) to contract resulting in a stiffening of the ossicular chain and a reduction in low-frequency sound transmission through the middle ear. This *acoustic reflex* serves to provide some protection of the inner ear from very loud sounds. It does not act instantaneously, however, and therefore does not provide protection against high-level impulsive noise (e.g., gunfire). (Additional information on the acoustic reflex is provided in Section 8 of this report.)

Abnormal conditions occurring between the outer ear and the stapes footplate can result in what are termed *conductive hearing losses* (e.g., a perforated eardrum, disruption of the ossicular chain, middle ear infections). Defects occurring beyond the middle ear in the cochlea or auditory nerve result in *sensorineural hearing losses* and these are generally not correctable although devices such as hearing aids can provide compensation in certain instances.

2.4 The Inner Ear

The inner ear includes the *cochlea* (or *auditory labyrinth*) which is the sensing element for hearing and the *vestibular labyrinth* (*semi-circular canals*) which senses head position and movement for the maintenance of balance. These are located within cavities in the temporal bone. The following discussion will concentrate on the end-organ of hearing, i.e., the cochlea.

*"This description is over-simplified but captures the function of the middle ear for those frequencies at which the mass and stiffness of the eardrum and ossicular chain are negligible. However, the picture is complicated by several factors. Above 2000 Hz, the tympanic membrane does not move as a unit and thus transmits energy less efficiently. In addition, the ossicular mass begins to impair transmission, and also a small amount of energy is dissipated by loose coupling between the individual ossicles. At low frequencies, the stiffness of the eardrum and ossicular chain can impair transmission. For example, unequal air pressure across the tympanic membrane, due to eustachian tube blockage and air absorption in the middle ear, can stiffen the tympanic membrane. Resonances of the middle ear cavity and of the mastoid and bulla cavities can also affect middle ear sound transmission." (Quoted from a manuscript copy of *The Auditory System: Acoustics, Psychoacoustics and the Periphery* by Robert A. Dobie and Edwin W. Rubel.)

The *cochlea* spirals through the dense temporal bone and is shaped something like a snail shell with about 2-1/2 turns. Figure 2-4 shows a section along the axis of the spiral (the spiral axis actually points anterolaterally rather than upward as shown). Along its entire length, the cochlea is divided into three compartments called the *scala vestibuli*, *scala media*, and *scala tympani*. In relation to the directional sense of Figure 2-4, the "upper" and "lower" compartments (*scala vestibuli* and *scala tympani*) are continuous at the top, or *apex*, and contain the same fluid, *perilymph*, which resembles cerebrospinal fluid. The *vestibular labyrinth*, which is not involved in the hearing process, is connected directly to the cochlea and also contains perilymph. The opening at the apex between the *scala vestibuli* and *scala tympani* is called the *helicotrema*. Each of these compartments is terminated at the basal end by membranous partitions called the *oval window* and *round window*, respectively, which separate these fluid-filled chambers from the air-filled space of the middle ear (refer to the previous Figure 2-1). As mentioned earlier, the footplate of the stapes is in direct contact with the membrane of the oval window. The round window acts as a "release valve" moving in response to the vibrations introduced at the oval window. An inward movement of the oval window membrane will result in an outward movement of the round window membrane.

The middle compartment, the *scala media* (or *cochlear duct*), is separated from the *scala vestibuli* by *Reissner's membrane* and from the *scala tympani* by the *basilar membrane*. This duct contains a fluid called *endolymph* which has a high potassium concentration and a high positive electrical potential relative to perilymph. (The vestibular labyrinth also contains endolymph.) The *organ of Corti* (named after Alphonse de Corti, an Italian count who was one of the first to describe its anatomy) rests on the basilar membrane and contains the sensory cells (*hair cells*) that convert the mechanical disturbances of the inner ear fluids into the electrical signals that are sent to the brain via the *auditory nerve*. There are three rows of *outer* hair cells and one row of *inner* hair cells (the estimates of the total number of hair cells in the human cochlea given by various authors range from 15,000 to 23,000). Figure 2-5 illustrates the arrangement of these sensory cells. A delicate group of hairs called *stereocilia* (or *cilia*) extends from the top of each cell. Some cells have up to 150 of these cilia. The cilia of the three rows of outer hair cells are attached to the tectorial membrane. The single row of inner hair cells does not appear to be directly attached to the tectorial membrane (Lim, 1980).

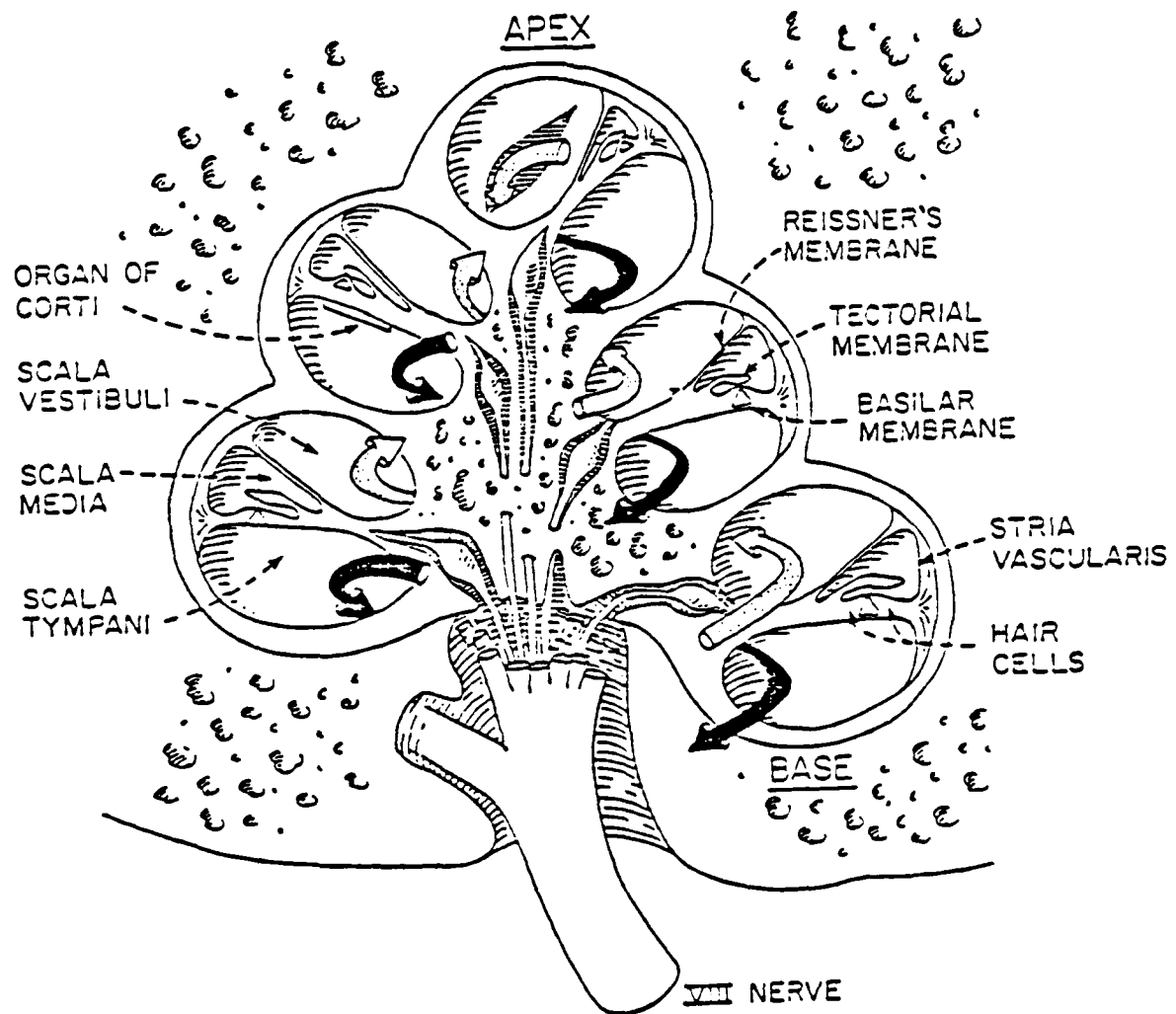


Figure 2-4

A section through the modiolus, or axis, of the cochlea shows its spiral orientation, with the three cochlear fluid compartments in each turn.
(Courtesy of R. A. Dobie.)

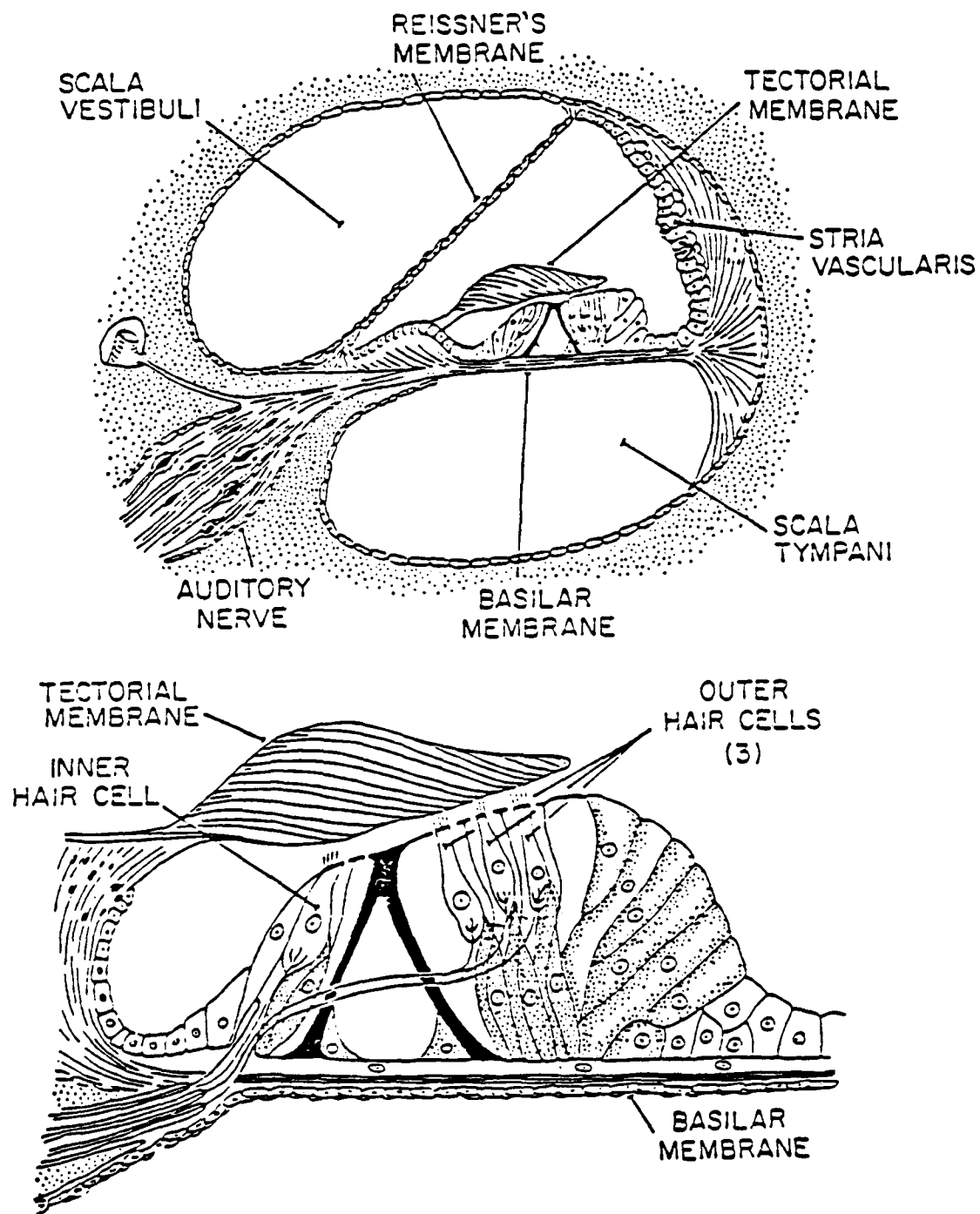


Figure 2-5

Cross section of the cochlear duct. The boundaries of the scala media with the scala vestibuli and the scala tympani are Reissner's membrane and the basilar membrane, respectively. (Courtesy of R. A. Dobie.)

When sound energy enters the cochlea by displacement of the stapes, the entire *cochlear partition*, including Reissner's membrane, the organ of Corti, and the basilar membrane, will be set into motion. An impulsive sound such as a click will create a wave that travels along the cochlear partition as illustrated in Figure 2-6. This wave traverses the cochlea in about 4-5 ms. It begins at high velocity which decreases exponentially as it travels toward the apex. (This is not a sound wave which would traverse the cochlea in about 20 μ s--rather it is analogous to a whipped rope attached at one end to a fixed object). The structure and mechanical impedance of the basilar membrane changes along its length. It is the narrowest, stiffest, and lightest at the basal end of the cochlea; and it is the widest, most flexible, and massive near the helicotrema. It is about 0.04 mm wide at the base and about 0.5 mm at the apex (Denes and Pinson, 1963). Because of these characteristics, the amount of movement or vibration at a specific point along the cochlear partition induced by a given sound will depend upon the frequency (or frequency components) of that sound. Figure 2-7 shows an example of the displacement pattern of the basilar membrane at several successive moments in time for a frequency of 200 Hz. The dashed curve in this figure is the envelope of maximum excursion at each point along the membrane. For different tones, the envelope maxima will occur at different positions as illustrated in Figure 2-8. For high frequencies, the peak amplitudes occur toward the basal end of the cochlea and, for low frequencies the peak responses occur nearer the apex (von Békésy, 1960).

The described mechanical characteristics of the cochlear partition allow it to function like a spectrum analyzer separating out the frequency components of a complex sound. However, in addition to these coarse mechanical properties, there is emerging evidence that some tuning may also be contributed by the mechanical and/or electrical characteristics of individual hair cells. Factors such as stereocilia height, diameter, stiffness, and number per cell, in relation to position along the basilar membrane, may be involved in this additional hair cell tuning process.

According to current theory, the motion of the basilar membrane in response to acoustic stimulation will bend the individual hair cells. Functionally, the tectorial membrane and basilar membrane appear to be hinged at different points on the medial wall of the cochlea as illustrated in Figure 2-9. Upward or downward movement of the cochlear partition bends the stereocilia at the point where the cilia meet the hair cell surface. (As mentioned earlier, the inner hair cell stereocilia are not directly attached to the tectorial membrane. They may be bent by subtectorial fluid currents rather than by direct contact with the tectorial membrane.) The bending of the stereocilia opens and closes ionic

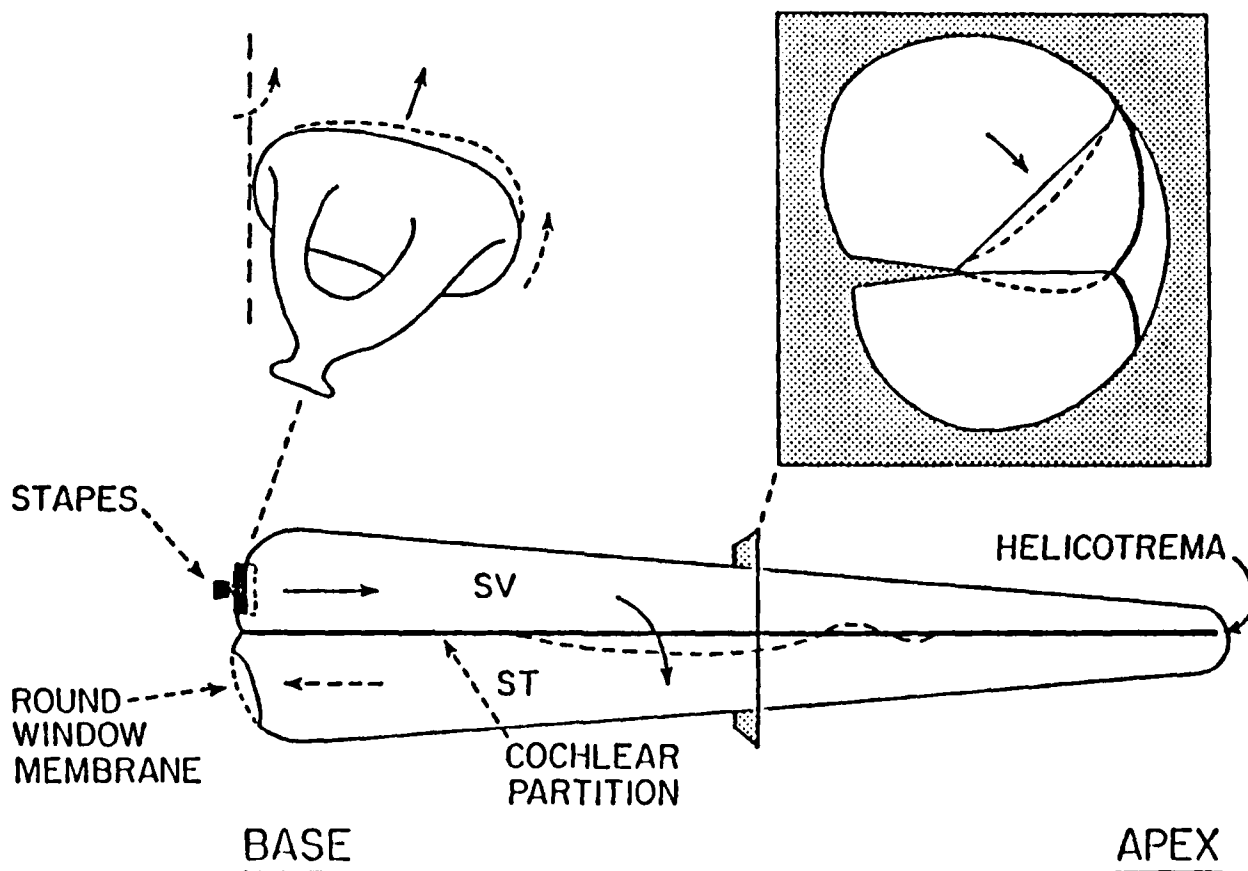


Figure 2-6

For ease of illustration, the cochlea is drawn "uncoiled." Inward movements of the stapes footplate cause compensatory outward movements of the round window membrane. For static pressure changes and very low frequencies, the pressure is transmitted from scala vestibuli to scala tympani via the helicotrema. For audible frequencies, the cochlear partition is displaced as indicated by the dotted line, in different places for different frequencies. (Courtesy of R. A. Dobie.)

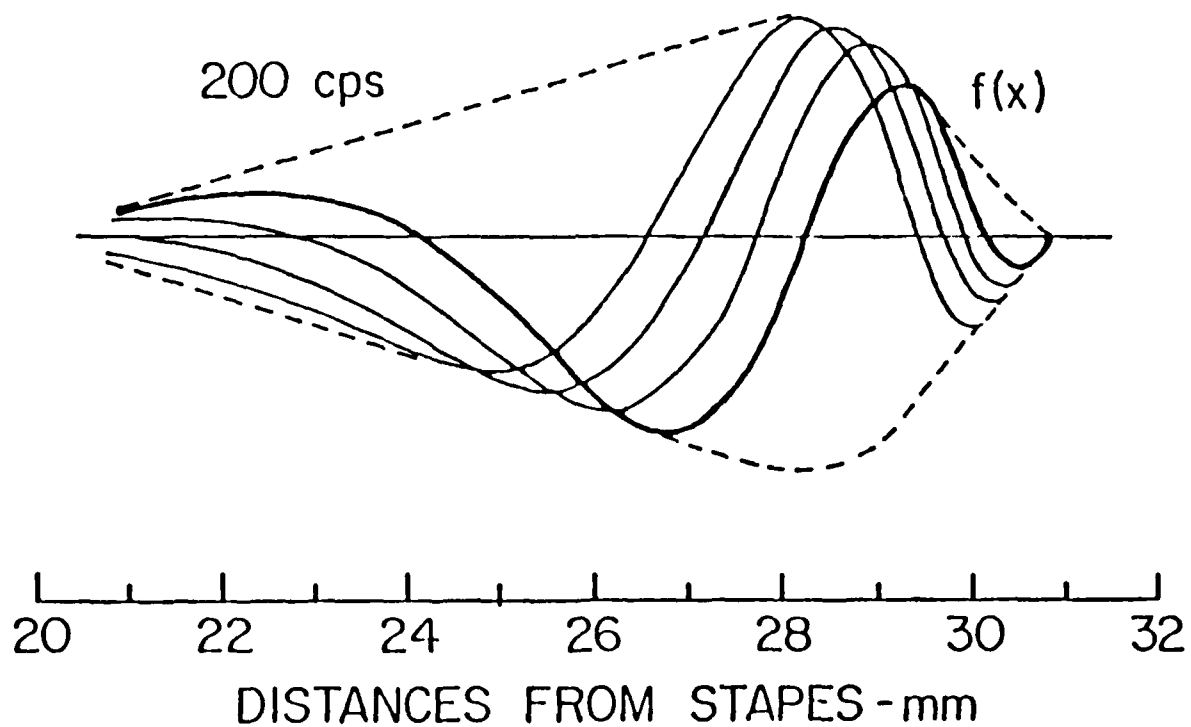


Figure 2-7

Each solid curve indicates the displacement of the basilar membrane at a particular point in time, in response to a 200 Hz tone. The darker curves occur later in time and show the progression of the traveling wave from base to apex of the cochlea. The dotted line indicates the envelope of displacement for this tone, i.e., the maximum displacement for each point along the basilar membrane. The actual excursions are many times smaller (relative to the length of the basilar membrane) than illustrated here. (Courtesy of R. A. Dobie.)

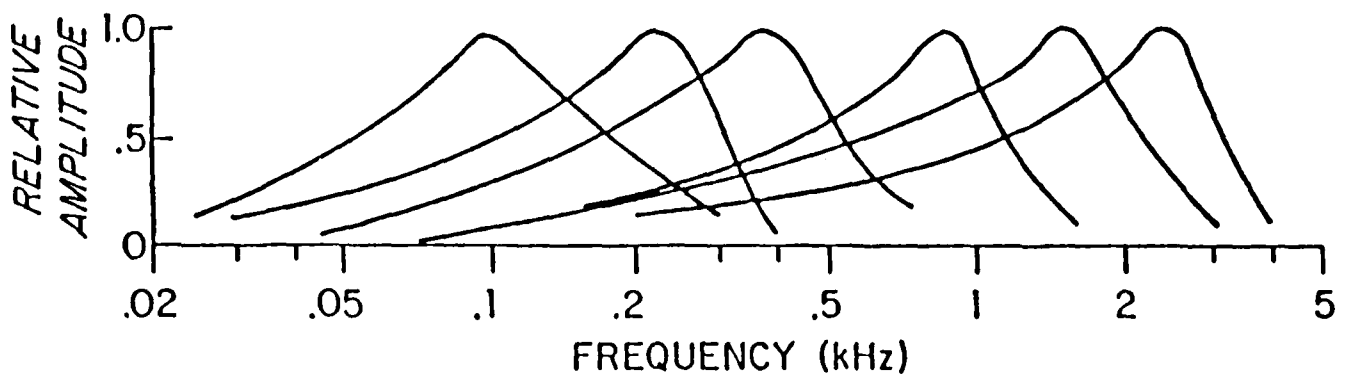


Figure 2-8

Each curve shows the response for a given point along the basilar membrane to tones of varying frequency. The curve farthest to the right is for a point near the midpoint of the cochlea and shows maximum response to about 2.5 kHz, gradually decreasing response to lower tones, and sharply reduced response to higher tones. The curves to the left are for progressively more apical locations. (Courtesy of R. A. Dobie.)

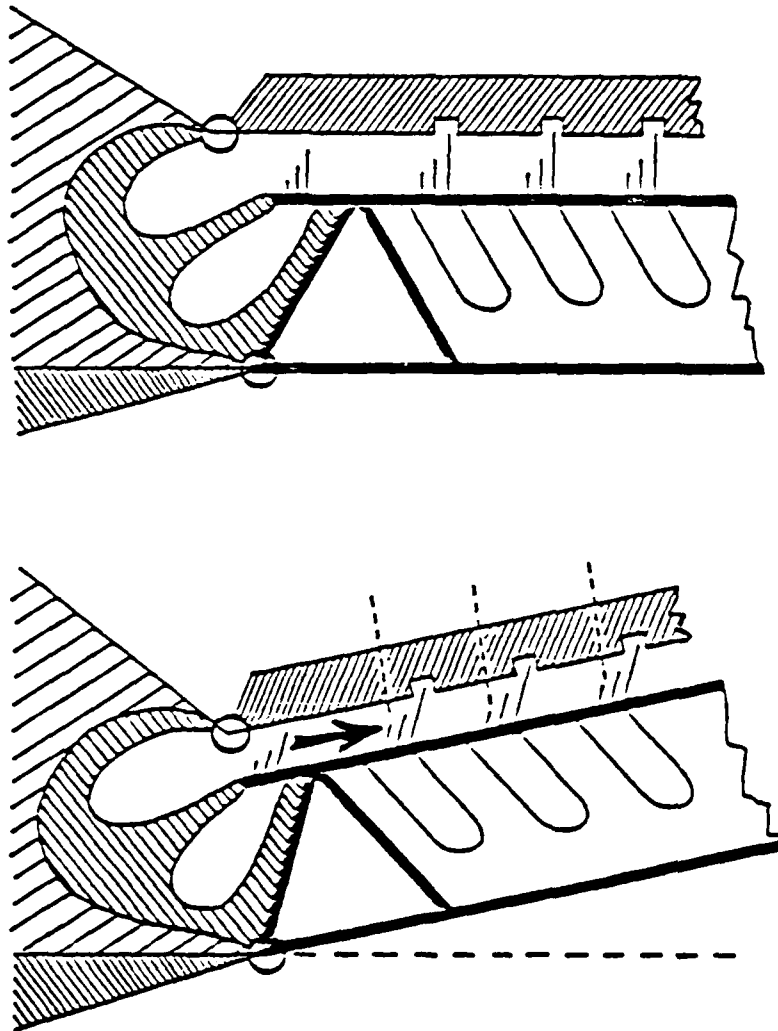


Figure 2-9

This diagram shows how an "upward" (toward scala vestibuli) displacement of the cochlear partition can create a shearing force tending to bend outer hair cell stereocilia in an excitatory direction. (Courtesy of R. A. Dobie.)

channels which appear to be located near the cilia tips (Hudspeth, 1983)--refer to Figure 2-10. Because of the large electrical potential difference between the endolymph (electrically positive re perilymph) and the hair cell interior (negative re perilymph), potassium ions are driven into the cell depolarizing it. This depolarization opens voltage-dependent calcium channels near the base of the cell which then initiates fusion of synaptic vesicles with the synaptic specialization at the base of the hair cell (again refer to Figure 2-10). Neurotransmitter release then effects spike initiation in the afferent (toward the brain) neuron. As the sound level is increased above threshold, the firing rate will increase, thus providing stimulus *intensity* information to the brain.

The inner hair cells appear to be the primary sensory receptors in the cochlea receiving most of the afferent innervation. The outer hair cells, which receive little afferent innervation but most of the efferent (from the brain) innervation, are thought to be primarily effector or motor structures functioning to tune the cochlear partition. It may be that this feedback activity serves to regulate outer hair cell length, tension, or other mechanical properties of the stereocilia which in turn affects the tuning of the organ of Corti. A loss of outer hair cells, therefore, can result in a significant hearing loss even though the inner hair cells are the primary sensors. (The outer hair cells appear to be more susceptible to noise-induced damage than the inner hair cells.)

Temporary or permanent hearing loss can occur as a result of acoustic overstimulation of the cochlea. Extremely loud sounds such as impulse events can cause direct mechanical injuries such as tears in the various membranes of the cochlear partition, or separation of the organ of Corti from the basilar or tectorial membranes. Metabolic exhaustion can also cause hair-cell injury at lower acoustic intensity levels when noise exposures extend over longer periods of time. In the underwater environment the tympanic pathway becomes significantly less efficient as a conductor of sound because the middle ear is designed to match impedances from air to cochlear fluid and it actually induces a mismatch of impedance for water-borne sound. Therefore, water-borne sound is primarily conducted into the inner ear by the mechanism of bone conduction through the skull. Even though the ear is less sensitive to a given sound pressure in water than it is in air, it can be damaged in much the same way if the acoustic levels are sufficiently high. The differences between underwater and in-air hearing sensitivity will be discussed in later sections of this report.

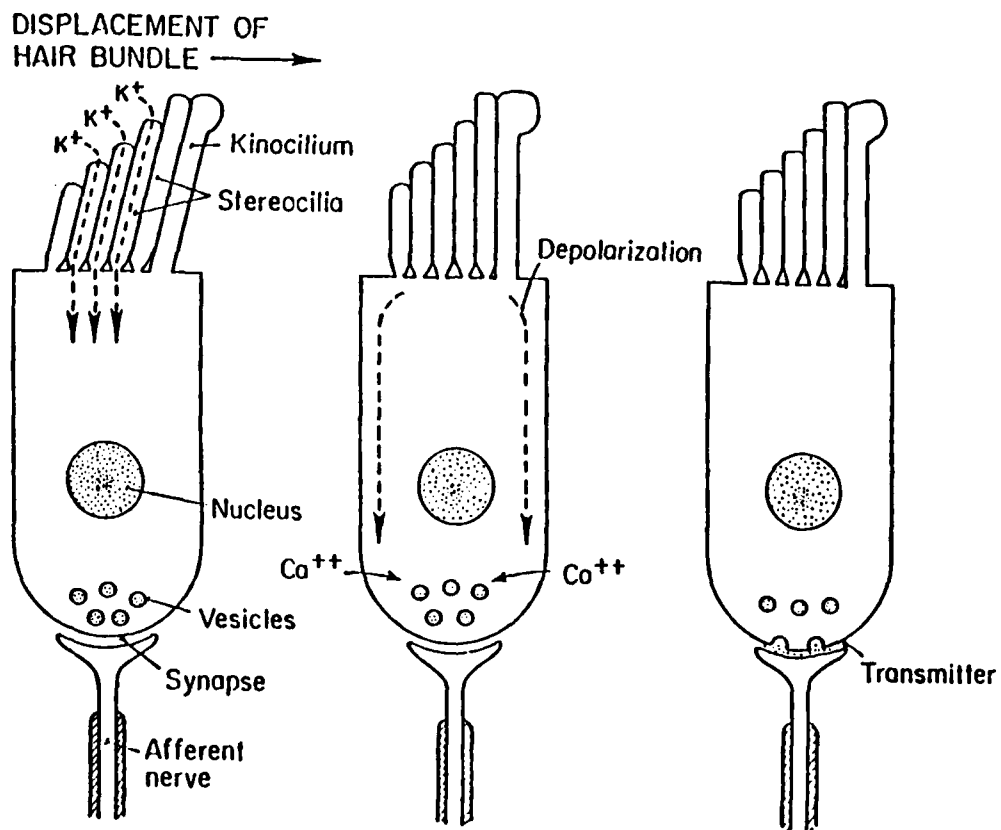


Figure 2-10

Deflection of the hair bundle toward the tallest row of stereocilia opens poorly-selective cationic channels near the stereocilia tips. Influx of potassium depolarizes the cell. Voltage-sensitive calcium channels open in turn, permitting neurotransmitter release across the synapse to the afferent neuron. (Courtesy of R. A. Dobie.)

3. SOUND LEVEL REFERENCE VALUES

One of the problems encountered when conducting a review of research literature dealing with a topic such as divers' hearing is that different investigators have used different sound level references when presenting their results. This makes it difficult to directly compare data from similar experiments, or to relate data such as those obtained from in-water experiments to those obtained from in-air experiments. In some instances, authors have neglected to specify the reference being used. The use of different references is caused in part by the evolution of conventions in the scientific community (e.g., mks replacing cgs as the accepted system of units), and in part by the background of the investigator (e.g., sonar or air acoustics).

Historically, the sonar community has employed either 1 dyne/cm^2 (1 microbar) or, more recently, 1 micropascal (μPa) as the reference sound pressure for calculating sound pressure levels (SPL) in dB. The air-acoustics community, on the other hand, has historically used $10^{-16} \text{ watts/cm}^2$ as the reference sound *intensity* value, or 0.0002 dyne/cm^2 * as the reference sound *pressure* value. For normal in-air conditions, these are effectively equivalent references. Either of these values represents the approximate threshold of hearing (intensity and pressure) for young adult ears in the most sensitive range of frequencies; e.g., 2,000 to 5,000 Hz. More recently, 20 micropascals which is equivalent to 0.0002 dyne/cm^2 has been adopted as the most universally used sound pressure reference for those involved in hearing research or noise control work, both for air and water environments. A reference value of $2 \times 10^{-5} \text{ N/m}^2$ (newton per square meter), which is also equivalent to 0.0002 dyne/cm^2 , has also been used by some investigators in their published work. *Throughout this report, we will use 20 μPa as the sound pressure level reference unless unique circumstances dictate otherwise, in which case we will so specify.* (From now on, "dB SPL" will mean "dB re 20 μPa .") As a convenience, Table 3-1 provides the method for converting levels using various reference values to a level in decibels re 20 μPa .

*Note: $0.000204 \text{ dyne/cm}^2$ was the in-air reference value used until some time after World War II. Early work in sonar also used this reference value.

Table 3-1. Conversion of sound levels using various references to sound levels re 20 μPa .

To Convert		Add or subtract according to sign
From	To	
SPL re 1 dyne/cm ²	SPL re 20 micropascals	+73.98 dB
SPL re 1 microbar (μb)	"	+73.98
SPL re 1 micropascal (μPa)	"	-26.02
SPL re 0.0002 dyne/cm ²	"	0
SPL re 2×10^{-5} newton/m ²	"	0
		<u>air</u> <u>sea water</u>
IL re 10^{-16} watt/cm ²	"	0 ^a +35.83 ^b
IL re 10^{-12} watt/m ²	"	0 ^a +35.83 ^b

^aThe conversion value of 0 dB is only valid when the characteristic impedance of the medium ($\rho_0 c$) is equal to 400 newton-sec/m³ (or 40 dyne-sec/cm³). The impedance $\rho_0 c$ for air will depend upon temperature and pressure. For example, at 22°C and 0.751 m Hg $\rho_0 c = 407$ newton-sec/m³. For these conditions, the intensity level would be 0.1 dB smaller than the sound pressure level. The exact relationship between intensity level and SPL is $\text{IL} = \text{SPL} + 10 \log_{10} 400/\rho_0 c$ dB, where $\rho_0 c$ has the units newton-sec/m³. (Example and equation from Beranek, 1986, pg. 14.)

^bThe conversion value of +35.83 dB is based upon a sea water density (ρ_0) of 1.026 gm/cm³ and a nominal sound speed (c) of 1490 ft/sec (1493.5 m/sec). The sound speed in water depends upon temperature, salinity, and pressure.

Some symbols and units:

watt: unit of electrical power, 1 watt = 1 joule/sec = 10⁷ erg/sec = 10⁷ dyne-cm/sec = 1 N-m/sec.

SPL: sound pressure level.

IL: intensity level.

dyne: unit of force, 1 dyne = 1 gm-cm/sec².

pascal: unit of pressure, 1 Pa = 1 N/m² = 10 dyne/cm².

newton: unit of force, 1 N = 1 kg-m/sec².

microbar: unit of pressure, 1 microbar = 1 dyne/cm².

rayl: unit of impedance, 1 rayl = 1 dyne-sec/cm³, 1 mks rayl = 1 newton-sec/m³.

4. COMPARISON OF IN-AIR AUDIOMETRIC DATA WITH UNDERWATER SOUND FIELD DATA

4.1 General

A number of in-water experiments have been performed in the past for the purpose of establishing the relationship between the thresholds of audibility underwater and in air. In general, underwater thresholds have been obtained by placing a swimmer or diver below the surface and having the subject listen for minimum levels of sound (e.g., tones of various frequencies) projected from a transducer positioned a meter or more away. In some of the experiments, the sound pressure level expected at the location of the subject's head has been calculated based upon the known source level of the projector, and the distance between the projector and the subject. In other experiments, a reference hydrophone has been used to measure the actual sound pressure level in situ. In contrast to these underwater "sound field" measurements, in-air hearing thresholds have frequently been obtained using standard pure-tone audiometric techniques involving a sound-proof booth, and an audiometer plus factory matched earphone. In one experiment, the signals being picked up by the underwater reference hydrophone were routed via appropriate electronics to earphones worn by the subject on the surface to obtain hearing levels. (The validity of these various approaches will be discussed later in this report.)

Some confusion exists in comparing underwater and in-air hearing performance when different techniques (audiometry versus sound field) are employed to measure the thresholds of hearing in the two media. Ideally, it would be desirable to make both kinds of measurements under free field conditions -- i.e., plane progressive waves and no reflecting boundaries -- and with negligible levels of ambient noise. These conditions can be approached in air by using an anechoic room whose boundaries effectively absorb sound. It is more difficult to meet these requirements in water since the surface is a good reflector and is always present. In addition, reflections can occur from other boundaries such as the bottom or the sides of a confined body of water like a pool or lake, and also from structures such as barges or supporting frameworks being used in the experiment. Standing wave patterns where regions of reinforcement or cancellation occur will be set up making it difficult to predict the sound levels within the field. Even "buddy" divers or the diver's own body and equipment (suit, hood, tank) can act as reflectors of sound and perturb the sound field. When a subject enters a sound field, his head also will perturb the field with sound diffracting around the head. For this reason, measurements of sound

fields are frequently made at the position that the listener's head will occupy, but with the listener not present.

In the absence of free-field measurements in air on the specific test subjects, audiometric data can be used in experiments intended to compare in-water and in-air hearing performance if the relationship between the two kinds of measurements (audiometer versus free-field) is known. In certain instances, hearing levels based upon earphone coupler pressures have been confused with, and used in place of, minimum audible field (MAF) data. Minimum audible pressure at the observer's eardrum (MAP) has also been confused with coupler pressure. It is important therefore to define these terms and to provide the information required to convert from the audiometer to the equivalent in-air free-field situation.

4.2 Threshold of Audibility

In dealing with the subject of hearing, the term *threshold* is frequently encountered. There are thresholds of audibility, discomfort, feeling, tickle, pain, and damage. Some authors consider the *threshold of hearing* to be synonymous with the *threshold of audibility* (Harris *et al.*, 1979, pg. 8-4). Others consider the term *thresholds of hearing* to include *thresholds of audibility*, and *thresholds of tolerance* such as pain, damage, etc. (Beranek, 1986, pg. 394-397). In this report, the term threshold of audibility will be used to represent the minimum pressure for a specified sound (in an otherwise quiet environment) that will evoke an auditory sensation in an individual a certain percentage of the time (usually 50 per cent). If the word *threshold* is used alone, it will normally mean *threshold of audibility*. The threshold of audibility will vary from individual to individual, and depends upon frequency and the manner in which sound is presented to the listener (e.g., earphones, free-field face on, free-field versus azimuth or elevation, monaural or binaural).

4.3 Minimum Audible Field (MAF)

The Minimum Audible Field, or MAF, is the average free-field sound pressure level for pure tones (expressed in dB) at the threshold of audibility for a large number of young adults (e.g., 18-30 years) having normal hearing; i.e., no known hearing abnormalities, no ear disease, no exposure to excessive noise. The sound pressure measurements are made in the absence of the listener but at the position the subject's head will occupy. Threshold measurements are made with the subject facing a sound source placed at a distance of 1 m or greater and listening with both ears (binaural). Measurements are

generally made in an anechoic room. An internationally accepted standard MAF curve (ISO R226-1961) is shown in Figure 4-1. Killion (1978) has suggested a modification to the low frequency portion of the standard MAF curve based upon a number of investigations covering the period from 1933 to 1976. He states, "Five out of six laboratories obtained results indicating the normal binaural MAF at 100 Hz is within 2 dB of 33 dB SPL. This is discrepant from the 25 dB SPL at 100 Hz given in ISO R226-1961." His suggested modification to the ISO curve is also shown in Figure 4-1.

4.4 Minimum Audible Pressure (MAP)

Historically, the term *Minimum Audible Pressure* or MAP was originally used to indicate the sound pressure level at the observer's eardrum at the threshold of audibility. The eardrum pressures are in general higher than the MAF values because of effects such as sound diffraction around the head, ear canal resonances, and focussing and resonance effects of the external ear. These effects are minimal at low frequencies. The differences are greatest in the frequency range of 2,000 to 5,000 Hz as shown in Figure 4-2 (the ear canal resonance effect alone produces an increase in SPL at the eardrum relative to the ear canal entrance of about 10 dB in the frequency range of 3 to 4 kHz). Unfortunately, the term MAP has also been used when referring to earphone coupler pressures (described below) and this probably has contributed to the confusion regarding, and misapplication of, the various terms. In this report, we will restrict the use of MAP to apply to eardrum pressures and, in accordance with the terminology used by Killion (1978) will use the term MAPC to indicate the minimum audible pressure at each frequency produced by a particular earphone (at audiometric zero) and measured by a specified coupler (e.g., National Bureau of Standards NBS-9A coupler).

4.5 Minimum Audible Pressure as Measured by a Standard Coupler (MAPC)

An audiometer is an instrument which measures at selected frequencies the audibility threshold level of an individual (called hearing threshold level or just hearing level in the field of audiometry) in comparison with a standard reference threshold typical of normal hearing for young adult ears. The 0 dB setting of the audiometer dial at each frequency corresponds to the reference threshold SPL at that frequency. The purpose of the audiometric test generally is to identify deficiencies in hearing.

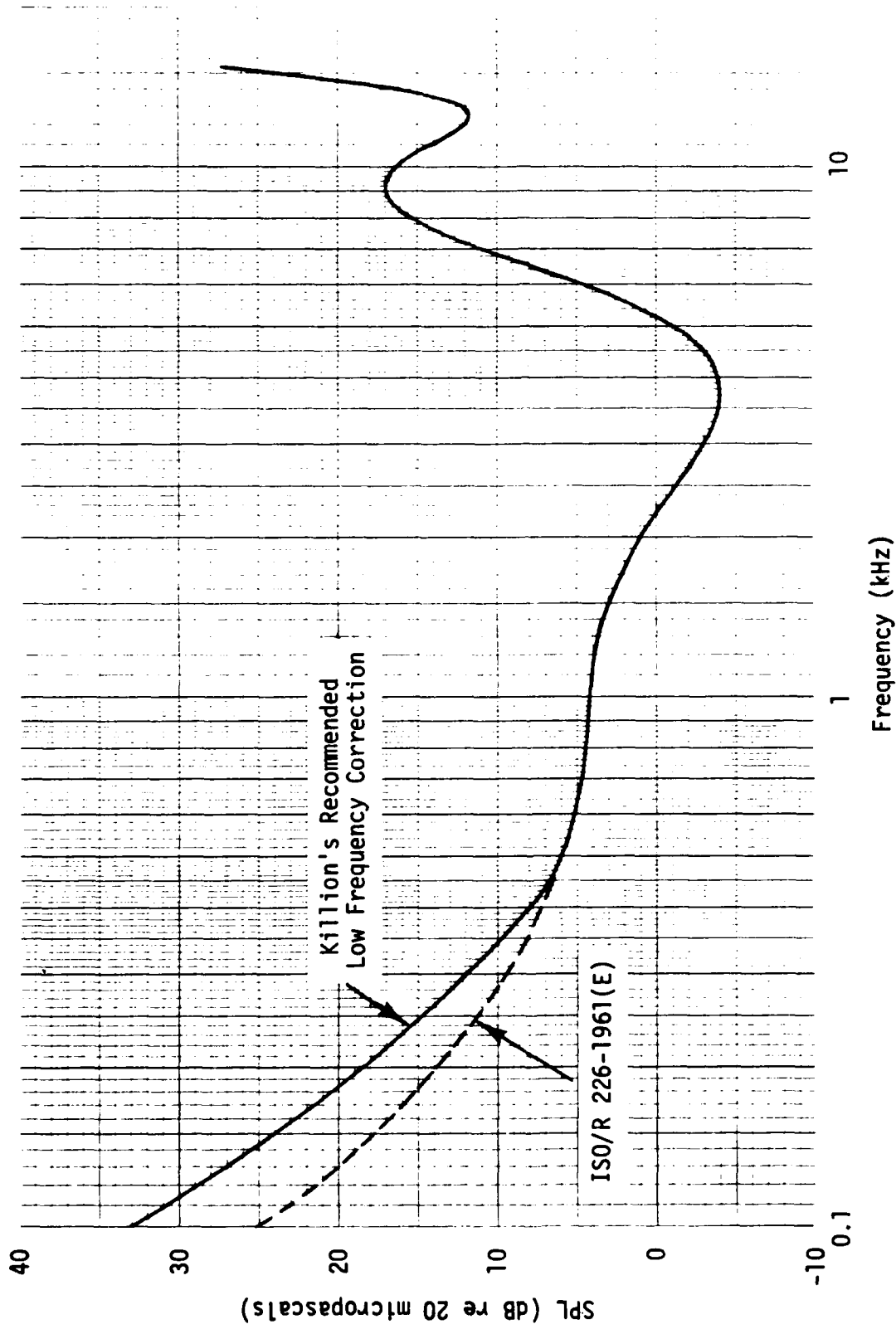


Figure 4-1

Normal binaural minimum audible field (MAF) for pure tones, from ISO/R 226-1961(E) but with Killion's (1978) recommended low frequency correction.

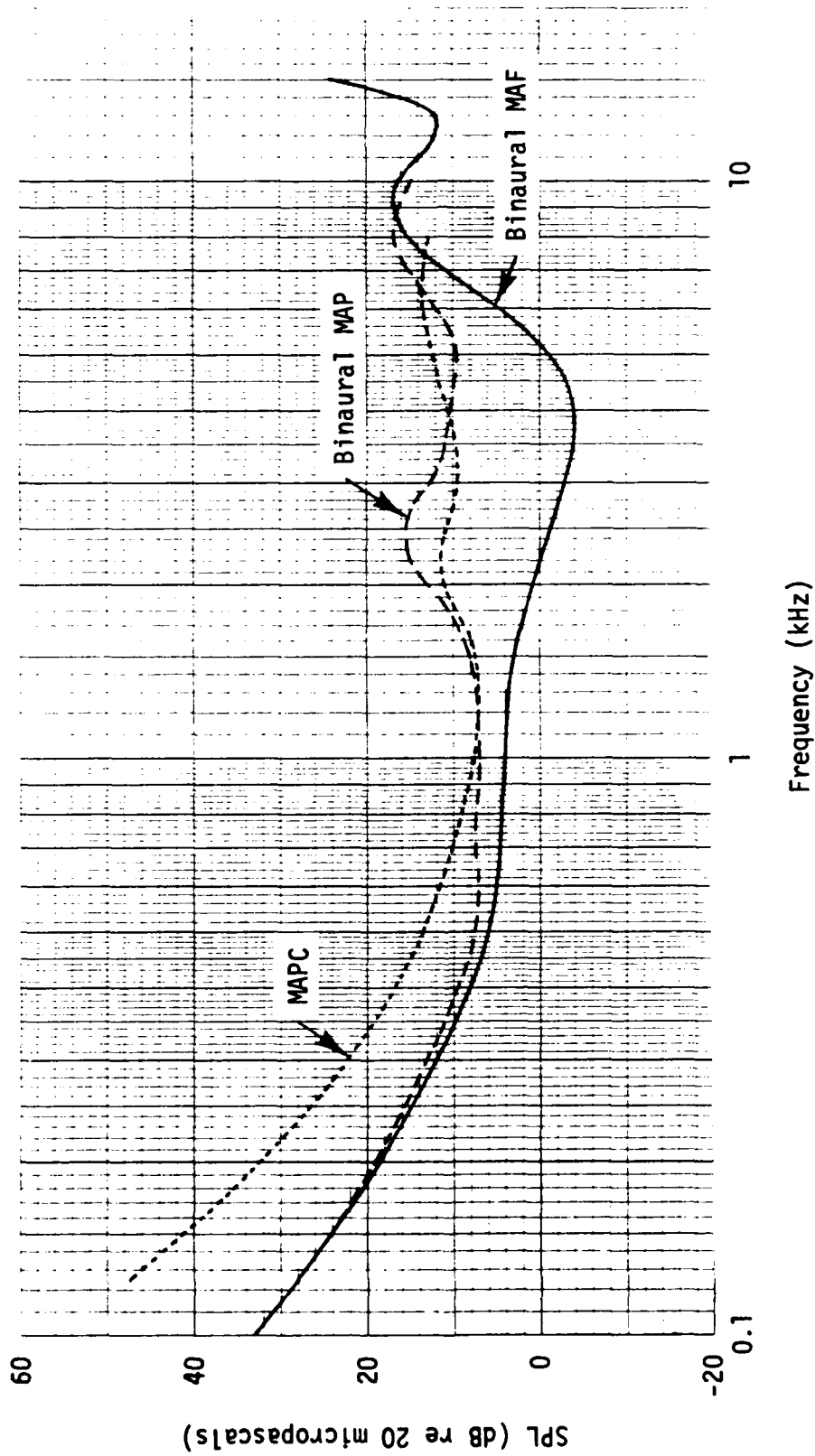


Figure 4-2

Comparison of binaural minimum audible field (MAF), binaural minimum audible pressure at the eardrum (MAP), and minimum audible pressure in a coupler (MAPC). MAF data from ISO/R 226-1961(E) but with Killion's (1978) low frequency correction. MAP data from Killion (1978); derived from free-field MAF. MAPC data from Harris (1979); for TDH-49 earphone and NBS 9-A coupler.

The basic audiometer consists of the electronics necessary to produce selected pure tones at known and repeatable levels, and earphones with cushions which are matched to the audiometer (preferably permanently connected). The audiometer must be calibrated periodically to insure proper performance. To measure the sound output of the earphone it is placed on the NBS 9-A coupler shown in Figure 4-3 or other accepted device such as an artificial ear. The measured output must agree, within specified limits, with standard reference zero sound pressure levels given for the particular type of earphone. Table 4-1 (after International Standard ISO 389-1975(E), Organization for Standardization, "Standard reference zero for the calibration of pure-tone audiometers"), lists the reference equivalent threshold sound pressure levels in the NBS 9-A coupler (RETSPL, which is equivalent to Killion's MAPC term) for eleven earphone types from five countries including the U.S. A column of data for the newer Telephonics TDH-49 and -50 earphones taken from Harris (1979), page 10-7, has been added on the right as a twelfth entry in this table. The spread in the data (maximum minus minimum) at each frequency is shown as the number in parentheses at the right side of the table. We see that the spread values are small -- e.g., 3 to 4 dB -- in the mid-frequency range (500 to 3,000 Hz) and increase at both the low- and high-frequency ends. As explained by Weissler (1968), the values differ because the sound pressure level (SPL) measured by the coupler "is dependent upon the electroacoustical properties of the earphone type and the acoustic load the coupler presents to the earphone. Thus, two different earphone types will generally produce different equivalent threshold SPL's in the same coupler. Also, the same earphone will produce different equivalent threshold SPL's in two different couplers." Although the RETSPL values are supposed to represent the same auditory threshold levels, they may also differ because of statistical variations arising from the samples (populations) employed in producing the results of Table 4-1.

The MAPC values for a representative earphone -- namely, the Telephonics TDH-49 -- have also been plotted in Figure 4-2 for comparison with the MAF and MAP data. There are significant differences between these curves. They are not equivalent, either in value or in physical meaning, and care must be taken in their use. It should be noted that the MAPC is in a sense a monaural term, whereas the MAF and MAP data of Figure 4-2 are for binaural listening. Binaural MAF thresholds are considered to be "better than" monaural thresholds by 2 to 3 dB (Harris *et al.*, 1979, page 8-5). Killion (1978) added a constant 2 dB when converting from MAP binaural to MAP monaural thresholds.

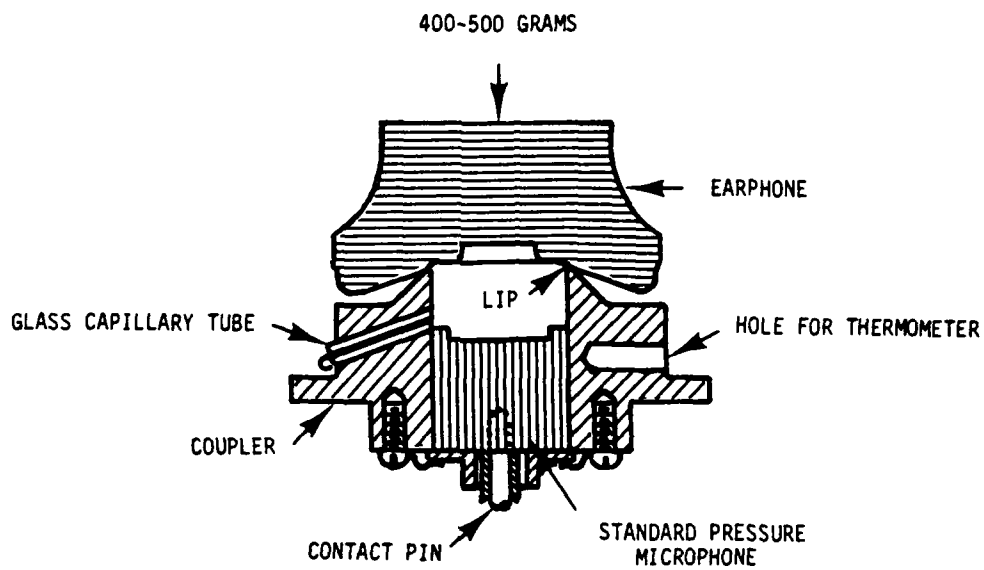


Figure 4-3

Illustration of NBS 9-A coupler. (After ANSI S3.6-1969 and Harris et al., 1979.)

Table 4-1. Reference equivalent threshold sound pressure levels (RETSPL or MPAC) in the 9-A coupler for various earphones.

Reference equivalent threshold sound pressure levels (dB re 20 μPa) (values rounded off to the nearest 0.5 dB)													
Freq Hz	Earphone ¹											Spread (dB)	
	Audio 15	Beyer DT 48 with flat cushion	S.T.C. 4026-A	W.E. 705-A	T.D. 6	Permoflux PDR 8 MX41/AR cushion	Permoflux PDR 1 Maico "Doughnut" cushion	Permoflux PDR 1 ADC case	Permoflux PDR 1 MX41/AR cushion	Permoflux PDR 10 MX41/AR cushion	Telephonics TDH 39 MX41/AR cushion ²		Telephonics TDH-49 and -50
125	48.5	47.5	51.0	45.5	54.0	44.0	44.0	46.5	46.5	51.0	45.0	47.5	(10.0)
250	28.0	28.5	30.5	24.5	32.0	25.0	25.0	26.0	26.0	28.5	25.5	26.5	(7.5)
500	12.0	14.5	13.5	11.0	14.0	11.5	11.0	10.5	11.0	10.0	11.5	13.5	(4.5)
1000	6.5	8.0	6.5	6.5	8.0	6.5	5.0	5.0	7.0	6.0	7.0	7.5	(3.0)
1500	----	7.5	7.0	6.5	8.0	5.5	----	5.0	7.0	6.5	6.5	7.5	(3.0)
2000	6.0	8.0	7.5	8.5	9.5	7.5	8.5	7.5	9.0	6.5	9.0	11.0	(3.5)
3000	8.0	6.0	8.0	7.5	10.0	8.0	----	6.5	10.0	9.0	10.0	9.5	(4.0)
4000	3.5	5.5	10.5	9.0	11.0	9.0	13.0	13.0	13.5	9.0	9.5	10.5	(10.0)
6000	14.5	8.0	13.5	8.0	17.5	17.0	----	11.0	8.5	18.5	15.5	13.5	(10.5)
8000	12.0	14.5	20.5	9.5	12.5	13.0	9.0	13.0	11.0	14.0	13.0	13.0	(11.5)

Note: The first eleven columns of data are from ISO 389-1975(E). The added TDH-49 and -50 column is from Harris (1979) and rounded. Spread values (maximum minus minimum at each frequency) are given in parentheses in the last column.

Notes from original reference:

¹"For these data to be valid the earphone should be placed both on the ear and on the coupler with its earcushion, with one exception; when calibrating the Beyer DT 48 earphone on the 9-A coupler, the cushion should be removed and an adapter used, as described by H. Mass and H. G. Diestel, in *Acustica*, 9, 61-64 (1959)."

²"In 1963 the filter cloth in the Telephonics TDH-29 earphone was changed, but matched to produce the same earphone response on the 9-A coupler. During the change about 1000 units were produced with an unmatched cloth. The data given in this International Standard are from several earphones manufactured both before and after 1963."

4.6 Caution -- U.S. Audiometric Standard Prior to 1970

Care should be taken when comparing audiometric data appearing in U.S. technical journals written prior to 1970 with those appearing after that year. This is an important point which can be easily overlooked. The reference MAPC values which were in use in the U.S. from the late 1930s until 1970 differed from those used after 1970 by amounts ranging from 6 to 15 dB. The two sets of values are given in Table 4-2 for the Western Electric earphone Type 705-A and the NBS 9-A coupler. The American Standards Association officially adopted the earlier reference levels in 1951 (ASA Z24.5-1951). The later standards were recommended by the International Organization for Standardization in 1964 (ISO Recommendation 389-1964), were officially adopted in the U.S. in 1969 (American National Standards Institute, Inc., ANSI S3.6-1969, June 19, 1969), and became effective September 1, 1970. The period from 1964 to 1970 may be particularly confusing -- ISO 1964 versus ANSI 1969 -- and for some technical journal articles it may be difficult to determine which reference MAPC values apply. Unfortunately, the available research on comparisons between underwater hearing thresholds of audibility and in-air thresholds bracket this time frame.

It should be noted that some efforts were made to begin using the ISO 1964 standards before they were officially adopted in the U.S. in 1969. Hallowell Davis and Fred Kranz, in an article in *The Journal of the Acoustical Society of America*, August 1964 provided an historical overview of the problem and discussed the advantages of using the ISO standards. They provided the following information regarding early adoption by various hearing organizations:

".... the Committee on Conservation of Hearing; the American Academy of Ophthalmology and Otolaryngology voted, on 8 December 1963, to adopt for its own use the new ISO standard values as of 1 January 1965. The Committee expresses the hope that the proposed new American Standard for Audiometers, incorporating the ISO reference-zero levels, will soon be approved and brought into general use. The American Otological Society voted a similar endorsement on 6 April 1964. Both organizations have adopted the ISO standard for their own use, beginning 1 January 1965. The American Otological Society will require that all audiograms accepted after that date for

Table 4-2. Reference MAPC values in effect in the U.S. before and after September 1, 1970.

Frequency Hz	MAPC Reference Values, dB re 20 μ Pa		Difference
	ASA Z24.5-1951	ISO 389-1964/ANSI S3.6-1969	
125	54.5	45.5	9.0
250	39.5	24.5	15.0
500	25.0	11.0	14.0
1000	16.5	6.5	10.0
1500	----	6.5	----
2000	17.0	8.5	8.5
3000	----	7.5	----
4000	15.0	9.0	6.0
6000	----	8.0	----
8000	21.0	9.5	11.5

- Note: (1) All values are rounded off to the nearest 0.5 dB.
 (2) ANSI S3.6-1969 standards became effective September 1, 1970.
 (3) Both sets of data are for the Western Electric earphone type 705-A and the NBS 9-A coupler.
 (4) Data from Appendix D of ANSI S3.6-1969.

publication in its Transactions be plotted according to the ISO scale.

In the June 1964 issue of *The Journal of the American Speech and Hearing Association*,⁴ the following special announcement is made: "The Executive Council of the American Speech and Hearing Association recently endorsed the International Reference Zero for pure-tone audiometers. On January 1, 1965 the Association will begin using the new reference scale exclusively in its journals and other technical publications.""

However, Davis and Kranz also cautioned that "it will be extremely important to label every audiogram clearly to indicate the scale according to which it is plotted" (i.e., ASA 1951 or ISO 1964). Again, unfortunately, in none of the many (reviewed) articles dealing with comparisons between underwater and in-air thresholds of audibility made during the period from 1964 to 1970 was there any mention of which standard applied to the audiometric information presented.

4.7 Conversion from Audiometric Data to Free-Field Data

In order to convert audiometric data to equivalent in-air free-field data, and thus allow comparison with hearing measurements made in underwater sound fields, the following transformations at each frequency can be made:

1. Hearing Level to MAPC (requires knowledge of earphone/cushion/coupler combination, and the standard that was in effect -- i.e., ASA Z24.5-1951 or ANSI S3.6-1969),
2. MAPC to ear canal entrance sound pressure level,
3. Ear canal entrance sound pressure level to pressure level at the eardrum, and
4. Eardrum sound pressure level to free-field level.

The data necessary to perform the first transformation have already been provided in a previous section; see Table 4-1. For example, the MAPC values for the Telephonics TDH 39 earphone from Table 4-1 will be used to illustrate the transformation process; they appear as the third column in Table 4-3. The subject's audiometric hearing level is, of course, also required (the second column in Table 4-3).

The fourth column in Table 4-3 lists the values which will allow the transformation from the TDH-39 MAPC values to ear canal entrance sound pressure levels. These values were obtained from Killion (1978), based upon Shaw (1966) who conducted measurements with a probe tube microphone on ten subjects and five different earphone types. They represent averages for nine of the ten subjects used in the experiment.

The fifth column provides the transformation values for ear canal entrance to eardrum, again obtained from Killion (1978) but based upon Shaw (1974). Shaw developed an average transfer function curve based upon earlier work of Wiener and Ross (1946), and Djupesland and Zwislöcki (1972), with an estimate above 8 kHz based upon work with a human ear replica by Shaw (1972).

The sixth column contains the data necessary to perform the transformation from the eardrum to the free field (at 0° azimuth). Shaw (1974) reviewed measurements from 12 studies and 5 different countries covering a 40-year period and involving 100 subjects to obtain a series of best-fit transformation curves as a function of frequency for various azimuth (sound arrival) angles. (He also summarized data on interaural sound level differences at the eardrum in his review.)

Each value in the seventh column is the sum of the corresponding values in columns 3, 4, 5 and 6, and represents the total transformation from the earphone to the free field at the specified frequency for monaural listening. The individual subject's hearing levels of column 2 (to be filled in) must be added to the appropriate column 7 values to obtain the monaural MAF for that subject. Since binaural listening is better than monaural listening, a constant 2 dB has been subtracted from column 7 to obtain the transformation values of column 8 for binaural MAF (a la Killion, 1978).

How well do these equivalent binaural MAF values derived from a number of experiments and studies dealing with the various step-by-step transformations agree with current MAF values based upon direct measurements in free sound fields; e.g., the MAF curve from ISO/R226-1961(E) as corrected by Killion (1978)? The latter MAF values are listed in the ninth column in Table 4-3. The tenth column, labeled Δ , contains the differences between the binaural MAF values derived from the two different approaches.

Table 4-3. Transformation of audiometric data to equivalent free-field data. (Numbers in parentheses are interpolated or extrapolated values.)

Frequency Hz	Subjects Hearing Level	MAPC for TDH-39 ¹	Earphone to Ear Canal Entrance ²	Canal Entrance to Eardrum ³	Eardrum to Free-Field ⁴	MAF Monaural ⁵	MAF Binaural ⁶	MAF ISO R226 Corrected ⁷	Δ
125		45.0	(-19.0)	0.0	(0.0)	= 26.0	24.0	28.5	-4.5
250		25.5	-7.0	0.2	(-0.9)	17.8	15.8	15.0	+0.8
500		11.5	2.5	0.7	-1.7	13.0	11.0	6.0	+5.0
1000		7.0	3.0	1.2	-2.6	8.6	6.6	4.2	+2.4
1500		6.5	2.5	2.4	-5.0	6.4	4.4	3.0	+1.4
2000		9.0	3.5	3.8	-12.0	4.3	2.3	1.0	+1.3
3000	Subject's Hearing Levels	10.0	-1.5	8.5	-15.4	1.6	-0.4	-2.9	+2.5
4000		9.5	-4.5	10.2	-14.2	1.0	-1.0	-3.9	+2.9
6000		15.5	1.0	3.7	-7.4	12.8	10.8	4.6	+6.2
8000		13.0	4.5	1.5	-1.8	17.2	15.2	15.3	-0.1
								average	+1.8

¹From ISO 389-1975(E), or ANSI S3.6-1969 Appendix F. Values depend upon earphone/cushion/coupler types.

²From Killion (1978) based upon Shaw (1966). Values depend upon earphone/cushion/coupler types.

³From Killion (1978) based upon Shaw (1974).

⁴From Killion (1978) based upon Shaw (1974). Values are for 0° azimuth (facing the sound source).

⁵Sum of columns 3, 4, 5 and 6.

⁶A constant 2 dB has been subtracted from the Monaural MAF values to account for the better sensitivity for binaural listening; a la Killion (1978).

⁷From Killion (1978). This column is compared with the preceding column (MAF Binaural) to obtain the final column labeled Δ . The latter two MAF columns should be the same if the MAPC and MAF/ISO values truly represent similar populations and if all transformations are perfect. The relatively small Δ 's suggest that the various transformations may be reasonably accurate.

In the mid-frequency range -- 1,000 to 4,000 Hz -- the agreement is within +1 to +3 dB, the positive sign indicating that the earphone derived MAF values are greater than the free-field MAF values. The Δ 's over all frequencies range from -0.1 to +6.2 dB with the average being +1.8 dB. There is a slight overall positive bias between the two sets of data, although the average difference is small enough to suggest that the various transformations are *reasonably* accurate.

In summary, the conversion of audiometric data to equivalent free-field data can be accomplished by performing the transformations just described of the hearing levels for an individual subject (or average levels for a group of subjects); or, assuming that each subject's ears are reasonably well matched, one can merely adjust the ISO/R226 curve (corrected) by the appropriate hearing levels (individual or group). The differences between the two approaches will not be large and, if necessary for a given application, the more conservative of the two sets of numbers can be used.

5. REVIEW OF EXPERIMENTS ON THE THRESHOLD OF AUDIBILITY UNDER WATER

5.1 General

In 1943, Sivian theoretically estimated that the threshold of audibility under water at a sound frequency of 1,000 Hz should be 45-55 dB above 0.0002 microbar.* He conducted a few measurements on 3 subjects in a swimming pool at 1,000 and 3,000 Hz and obtained average threshold values which were not inconsistent with his theoretical estimate (the values were 44 and 49 dB SPL respectively). Because of the limitations of both the theoretical analysis and the experimental work, Sivian recommended that further measurements be performed.

A number of experiments by various investigators have been performed since that time. The results obtained have not been sufficiently consistent from one set of measurements to the next to clearly establish the differences between in-air and in-water hearing. In this section of the report, each of the experiments is evaluated as to potential weaknesses or areas of uncertainty in an effort to establish their validity and to better define the air-versus-water hearing relationship.

Table 5-1 lists the investigators and experiments conducted beginning with Sivian's initial work in 1943.

5.2 Sivian (1943, 1947)

Sivian's work was directed toward answering the question as to whether or not a submerged swimmer could hear sounds generated in the air overhead. He estimated that a 45-55 dB loss in audibility for listening in water versus listening in air might be expected based upon theoretical considerations.

*Note: Sivian used the term *bar* which in earlier years was the term used for an acoustical pressure of 1 dyne/cm² which is today the microbar.

This section of the report was written by Paul C. Kirkland after consultation with Robert A. Dobie, Phillip A. Yantis, and Elbert A. Pence, Jr..

Table 5-1. Experiments on underwater thresholds of audibility.

Year of Article or Report	Reference	Investigators
1947 (1943)	"On hearing in water versus hearing in air," J. Acoust. Soc. Am. 19, 461-463 (Based upon 2 memoranda published in 1943)	Sivian, L. J.
1944	"Signalling and homing by underwater sound; for small craft and commando swimmers," Sound Report No. 19, Naval Research Laboratory	Ide, J.
1956	"Hearing in whales," Acta Oto-Laryngol., Suppl., 134	Reysenbach de Haan, F. W.
1957	"Underwater hearing thresholds," J. Acoust. Soc. Am. 29, 792-794	Hamilton, P. M.
1958	"Comparison of hearing thresholds in air and in water," J. Acoust. Soc. Am. 30, 1025-1029	Wainwright, Walter N.
1961	"Sensitivity of the water-immersed ear to high- and low-level tones," J. Acoust. Soc. Am. 33, 1376-1381	Montague, W. E. and Strickland, J. F.
1965	"Bone conduction, air conduction, and underwater hearing," U.S. Naval Submarine Medical Center, Memorandum Report No. 65-12, 8 October 1965	Smith, Paul F.
1967	"Underwater hearing thresholds in man," J. Acoust. Soc. Am. 42, 966-971	Brandt, John F. and Hollien, Harry
1969	"Underwater hearing in man: I. Sensitivity," U.S. Naval Submarine Medical Center, Report No. 569, 28 February 1969	Smith, Paul F.
1969	"Effect of air bubbles in the external auditory meatus on underwater hearing thresholds," J. Acoust. Soc. Am. 46, 384-387	Hollien, Harry and Brandt, John F.
1969	"Underwater hearing thresholds in man as a function of water depth," Communication Sciences Laboratory, University of Florida, CSL/ONR Report #16, August 1, 1969	Hollien, Harry, Brandt, John F. and Doherty, E. Thomas
1975	"Contribution of the external auditory meatus to auditory sensitivity underwater," J. Acoust. Soc. Am. 57, 1488-1492	Hollien, Harry and Feinstein, Stephen

A limited experiment was performed in a swimming pool 60' x 18' x 6'5" using 3 observers. A loudspeaker was positioned so as to project sound downward towards the surface of the pool. Each unclothed swimmer positioned his chin just out of the water for in-air measurements and stood upright on the pool bottom (weighted sandals) for in-water listening. One observer's ears were 9" below the surface and for the other two 15". The swimmers had to hold their breath for the underwater measurements. Data were obtained at two frequencies; 1,000 and 3,000 Hz. Figure 5-1 illustrates our understanding of the experimental setup based upon available descriptive information.

Sivian considered factors which could influence the underwater measurements. Background noise in the water which could cause masking was kept to a minimum by use of a quiet pool and by keeping the subjects motionless during the tests. The problem of unbalanced hydrostatic pressure on the eardrum, which might reduce audibility, was solved by conducting the tests near the surface and by efforts to equalize pressure via the Eustachian tubes. (If underwater hearing is primarily by bone conduction, this effect would not be important even if a residual pressure difference existed.) The effect of the observer's head and body upon the sound field in the vicinity of the air-water interface was also considered by Sivian. He felt that because the subject's body was positioned vertically and normal to the surface, that this effect would also be minimized.

This experiment involved a *direct* comparison of in-air and in-water hearing which inherently could have certain advantages over the use of different techniques in the two mediums (e.g., audiometry in air, versus free field in water). However, uncertainties and deficiencies exist. Sivian's 1947 article lacked information on the details of the experiment which were probably described more fully in the two memoranda on which the article was based ("Exchange of Acoustic Pressures and Intensities in the Air-Water System" of January 21, 1943 and "On Hearing in Water vs. Hearing in Air, with some Experimental Evidence" of March 8, 1943, submitted to the National Defence Research Committee, NDRC). Smith (1969), having access to Sivian's original memoranda, provided some additional details in his review of early research in underwater hearing.

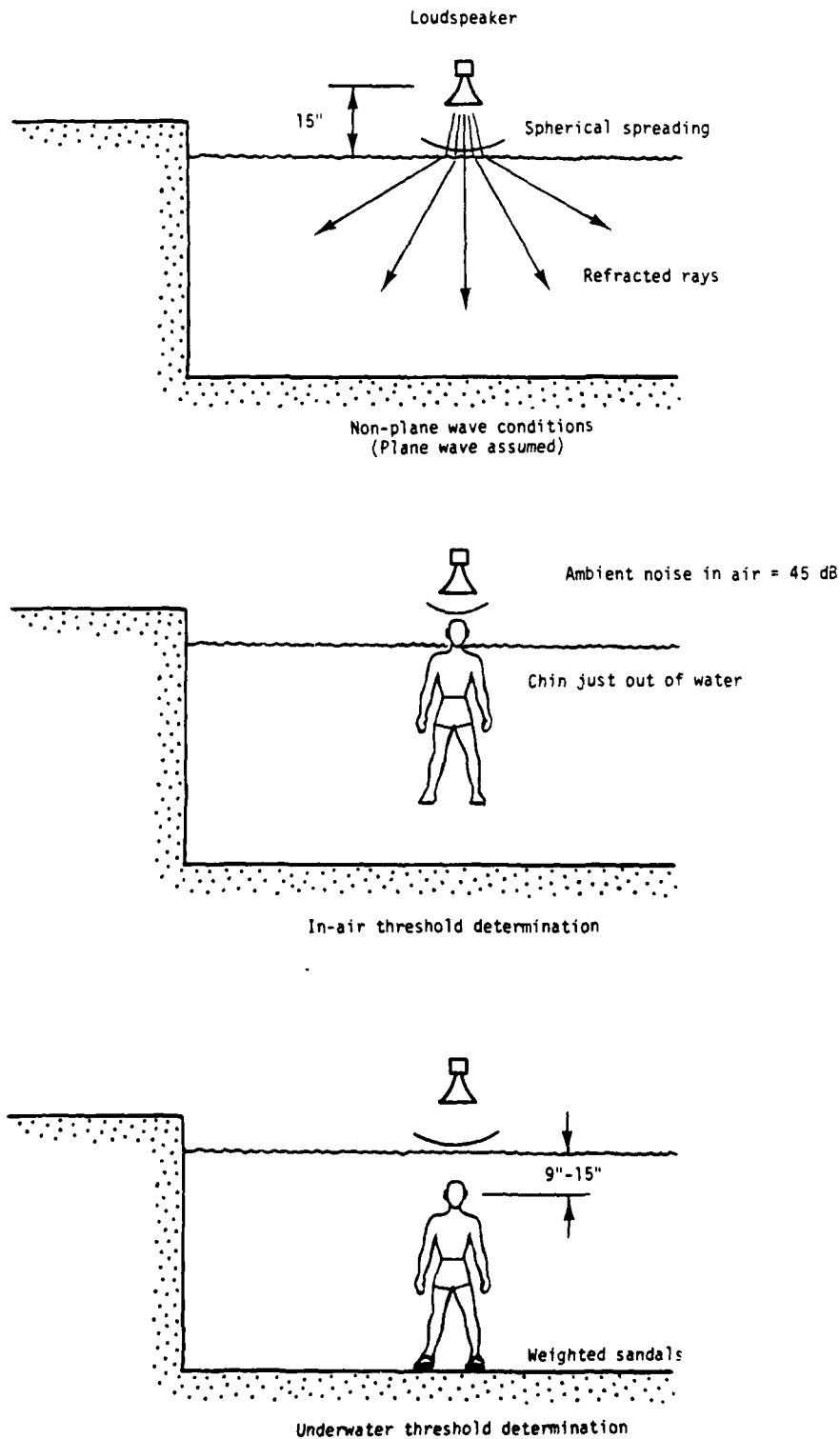
The additional information provided by Smith included the following:

"The tests were conducted in the early morning hours on a Sunday, so as to minimize interference by extraneous

Figure 5-1

Interpretation of Sivian's experiment (based upon available descriptive material).

60' x 18' x 6'5" Swimming pool
3 Subjects
1,000 and 3,000 Hz



noise. The sound source was a 12" moving coil loudspeaker which was mounted about 15" above the surface of the pool and driven by a 6-A audiometer."

He also indicated that

"... the (ambient) noise level in air, as measured by an RA-358 Sound Level Meter, was 45 dB. Underwater noise levels were not measured. The thresholds were recorded in terms of the attenuator settings on the 6-A audiometer. No physical calibrations were performed."

Sivian did not employ an underwater sound source nor did he make any measurements of the underwater sound field. The underwater tones were provided by acoustic transmission through the air-water interface of sound projected downward from a loudspeaker positioned 15" above the surface of the pool. Although much of the acoustic energy will be reflected away from this boundary, the acoustic pressure at the interface will be the same in water as it is in air (a boundary condition). Sivian, in his analysis of the problem, has described the situation as follows:

"... For simplicity, the air and the water are regarded as semi-infinite media, the only reflection taking place at their interface. The airborne sound is taken as a plane wave, and normal incidence upon the air-water interface is assumed. The complex voice sound is replaced with a sine wave, e.g., a 1000 c.p.s. tone. The free field pressure assumed is ... (for example) ... 5 bars r.m.s., and the r.m.s. pressure of this airborne wave at the interface is taken as 10 bars, i.e., practically complete pressure doubling caused by reflection is assumed.

The boundary condition at the interface is that the acoustic pressures in the air and in the water are the same: $P_a = P_w$. There is, therefore, propagated into our assumed semi-infinite water medium a progressive wave of 10 bars r.m.s. pressure, the same pressure as in the air above. The

commonly thought of "practically total reflection" of airborne sound striking a water surface, refers to the fact that the intensity of the waterborn wave is only ca. 1/900 of the intensity of the incident progressive airborne wave."

In the actual experiment, the airborne sound was not a plane wave but rather was emanating from the loudspeaker placed above the subject's position. Because of the higher sound speed in water as compared with the sound speed in air (e.g., 4900 ft/s versus 1130 ft/s), refraction would occur at the interface for all sound rays except the one normal to the surface, and the refracted rays would be bent away from the normal. Indeed, the critical angle is only about 13° for the in-air sound ray passing into the water medium (the critical angle is the angle of incidence corresponding to an angle of refraction of 90°). The effects of spherical wave spreading and ray bending at the interface would reduce the sound pressure/intensity at the underwater ear position significantly below the level corresponding to the plane wave assumption. In order to be heard underwater, the level in air would have to be higher than for a plane wave.

Another source of concern in this experiment was the relatively high ambient noise level in air as reported by Smith (1969) in his review; i.e., 45 dB SPL. This is the kind of background noise level (45 to 50 dB(A)) that is purposely incorporated into the design of open-plan offices in order to mask distracting sounds from adjacent work positions (Harris, 1979, page 24-11). This is far too noisy for valid audiometry work. Therefore, Sivian's in-air levels would be much higher than the actual thresholds of audibility for his subjects.

Although the sources of error described in the two preceding paragraphs tend to compensate each other, the actual individual error values and resultant error are difficult to predict. Considering these, and other factors such as the shallow pool with the possibility of interfering reflections and standing wave patterns, a large uncertainty in the results of this experiment might conceivably exist. Indeed, Sivian pointed out the "limited scope of the experiment and the broad assumptions made in the theoretical estimate" and "that further measurements, particularly in deeper water, are desirable.... ." In summary, Sivian's measurements are judged to be too limited to be included in a data base intended to establish accurate estimates of the differences between in-air and underwater thresholds of audibility.

5.3 Ide (1944)

John M. Ide of the U. S. Naval Research Laboratory conducted some underwater threshold measurements in 1944 as part of a study, "Signalling and homing by underwater sound; for small craft and commando swimmers" (NRL Sound Report No. 19, June 23, 1944). Unfortunately, we have not obtained a copy of this report for review. However, Ide's data were presented in Wainwright's (1958) paper for comparison with his own measurements, as well as in Smith's (1969) report (both are discussed in later sections). Ide's underwater and in-air threshold data, based upon these two references, are shown in Figure 5-2.

Smith (1969) reviewed Ide's report and noted a number of deficiencies:

"Ide failed to report many important methodological details. No information is given on how the SPL at the diver's head was estimated and controlled or on the specifics of the test procedure. Underwater ambient noise levels were not reported. AC hearing levels of Ss were not reported. Apparently, the tests were conducted at depths of three to six feet in water which was 35 to 40 feet deep. It was reported that "Audiometer-type tests" were used and Ss were three men listening underwater with the unaided ear."

The subjects were breath-holding swimmers. The signals employed were intermittent tones at selected frequencies from 100 to 6000 Hz.

In presenting his data, Ide also illustrated the "audiometric function for hearing in air." This latter curve appears to be similar to, but not exactly the same as, Sivian and White's (1933) monaural MAP curve which would be representative of minimum audible pressures at the eardrum and not binaural free-field data. (In their 1933 paper, Figure 10, page 313, Sivian and White presented average curves for monaural MAP, binaural MAF at 0° azimuth, and binaural MAF for random horizontal incidence. This was a well-known reference during the period of Ide's work.)

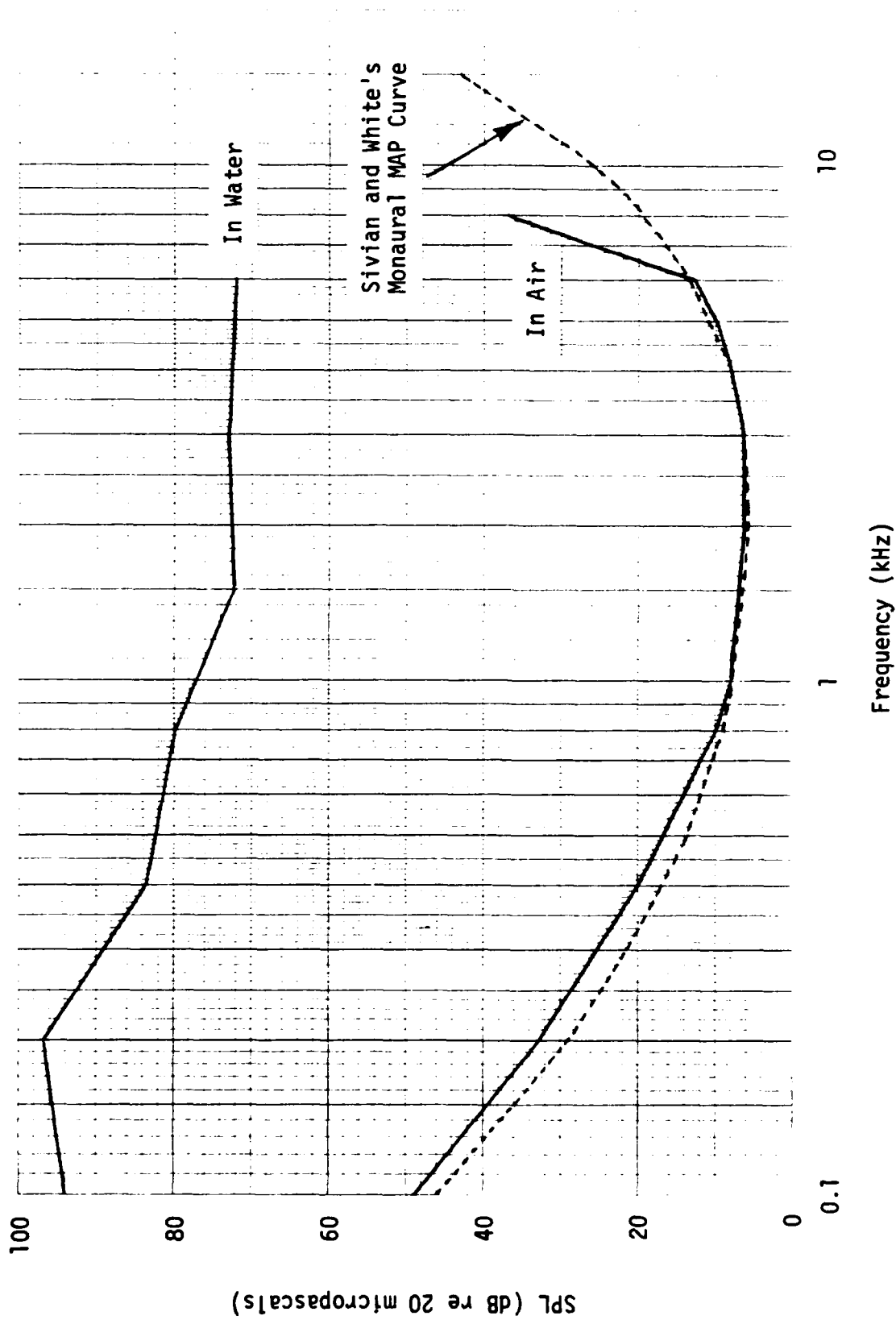


Figure 5-2

Ide's thresholds of audibility for in water and in air.
Data from Wainwright (1958) and Smith (1969).

Ide's underwater threshold measurements were the highest of any of the other investigators at frequencies of 1 kHz and below. At higher frequencies, they intermingled with the other measurements. Because of the lack of specific details concerning this experiment, we must question the accuracy of the results and therefore would not include the information in a data base on underwater thresholds of audibility.

5.4 Reysenbach de Haan (1956)

In his report on a study of hearing in whales, Reysenbach de Haan describes an experiment on the behavior of the human ear under water. The purpose of the experiment was related to the frequent comparisons in the report between the hearing of land mammals and aquatic animals, man being taken as representative of the former. His setup is illustrated in Figure 5-3.

The tests were performed in a large pool (assumed to be natural) described as having a depth of 18 m and a surface area of about 120,000 m². The author believed that, "owing to its form, dimensions, and configuration of bottom and banks, the pool could be considered a free-field environment for acoustic measurements" (surface reflection effects will be discussed shortly).

Three subjects were employed. Each observer was positioned 25 m away from a sound source suspended from a pontoon 3 m under the surface of the water. The subject's ears were just under the surface for the measurements. An "underwater sound pressure meter" was suspended at 3 m depth and 5 m away from the projector in the opposite direction from the observer. (It is not known why the sound pressure measurements were not made at the subject's head position. Possibly the reason was equipment or facility limitations rather than choice.) The maximum response axis of the sound source was directed toward the observer who listened to a tone. The sound level was slowly reduced until the observer could no longer hear the tone (this is not an ideal method for making such psychoacoustic measurements) at which time he signaled by hand to test personnel on the pontoon. The projector was then turned 180° in azimuth and directed toward the underwater meter to obtain a measurement of sound pressure. This value was then divided by 5 (the ratio of the two ranges, 25 m and 5 m) to obtain an estimate of the sound pressure at the subject's position. Data were obtained for the two conditions of air in the auditory canal and water in the auditory canal.

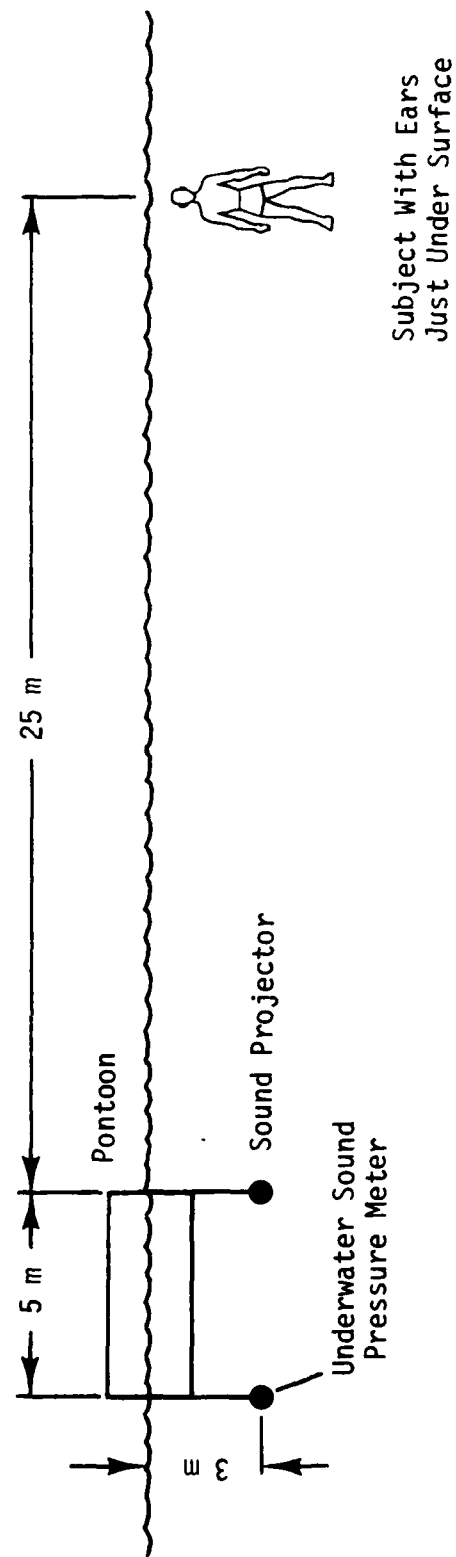


Figure 5-3

Experimental setup for the determination of underwater thresholds of audibility. (After Reysebach de Haan, 1956.)

The author was cognizant of a potential problem with reflections off of the surface near the subject's position for the hearing measurements, and off of the pontoon for the pressure measurements. By having the subject's head just under the surface (so that the total length for the reflected sound ray path was not much greater than the direct path length; e.g., significantly less than one-half of a wavelength difference), he assumed that the sound pressure at the subject's ears would be effectively doubled. It appears that he may have neglected the fact that the phase of the reflected wave is shifted 180° at a water-to-air boundary and therefore the sound pressure, rather than doubling, could approach zero (total cancellation) under certain geometric conditions--the familiar Lloyd mirror or image-interference effect.

Figure 5-4 shows the Lloyd mirror curve as a function of normalized range for a surface reflection coefficient of unity (corresponding to a smooth surface). If we calculate values for the abscissa term $\lambda r/4d_1d_2$ at the frequencies of interest, we can obtain estimates of the sound pressure level decrease (below Reysenbach de Haan's assumed "doubling") caused by the image interference effect. The results of such calculations are shown in Table 5-2. The fifth column in this table lists the values for the reduction in sound pressure level at the subject's position caused by the Lloyd mirror effect for the assumed geometric conditions of the experiment. The sixth (last) column lists the total correction required and includes the removal of the 6 dB doubling introduced by Reysenbach de Haan. We see that the corrections can be quite large, particularly at the lower frequencies such as 1, 2, and 4 kHz where the total corrections are -26, -20, and -14 dB respectively.

Figure 5-5 shows Reysenbach de Haan's original data for the two conditions of air and water in the auditory canal. (Although there appears to be a difference between these two conditions, subsequent investigators have found little if any difference. This subject will be discussed elsewhere in the report.) Also shown in the figure is a curve described as "the threshold for binaural hearing in the free field in the air, as measured for normal persons by Sivian and White." (Note that this is a smooth curve that does not dip below 0 dB over any portion of the frequency range.) Reysenbach de Haan's list of references, however, does not include Sivian and White. If we assume that the data came from their well-known 1933 paper, then it would appear that the curve shown in Figure 5-5 represents Sivan and White's monaural MAP curve, possibly adjusted slightly for binaural listening; *and not MAF data*. That is the only "smooth" curve presented in the Sivian and White paper that does not go below 0 dB sound pressure level in the mid-frequency range.

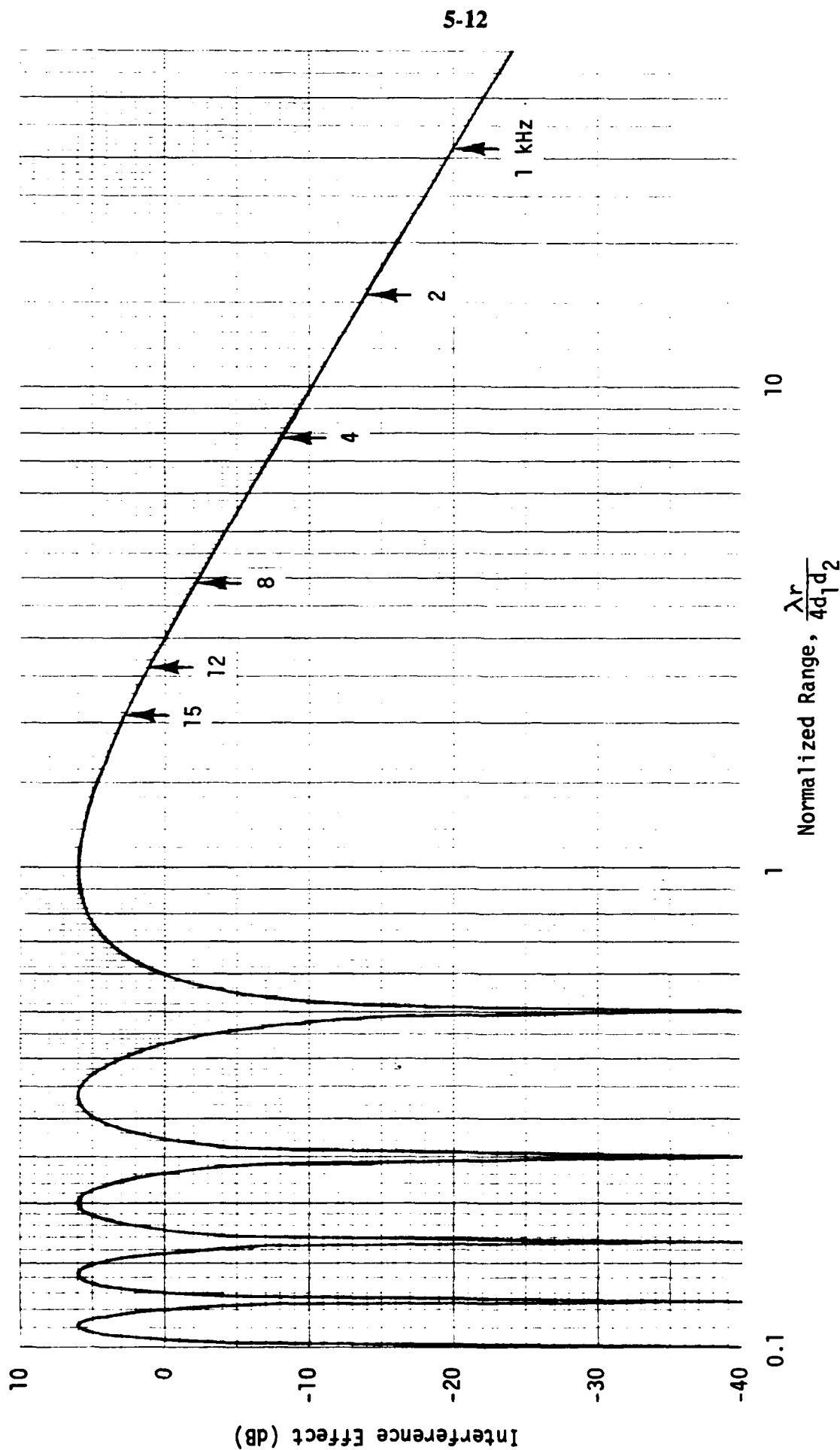


Figure 5-4

Surface reflected image interference curve for a reflection coefficient of unity as a function of normalized range. (After Urlick, 1967, page 112.) Arrows represent interference values for specific frequencies and experimental geometry used by Reysenbach de Haan.

Table 5-2. Correction to Reysenbach de Haan's data for smooth surface conditions and ear depth of 0.1 m*.

λ = wavelength corresponding to frequencies employed
(1, 2, 4, 8, 12 and 15 kHz)

r = horizontal range, source to receiver (25 m)

d_1 = depth of source (3 m)

d_2 = depth of receiver (ear; assume 0.1 m)

c = sound velocity (assume 1500 m/s)

Freq (kHz)	λ (m)	$r/4d_1d_2$ (m ⁻¹)	$\frac{\lambda r}{4d_1d_2}$	Interference effect from Figure 5-4 (dB)	Total correction (includes removal of assumed 6 dB doubling)
1	1.5	20.833	31.25	-20	-26
2	0.75	"	15.63	-14	-20
4	0.375	"	7.81	-8	-14
8	0.1875	"	3.91	-2	-8
12	0.125	"	2.60	+1	-5
15	0.1	"	2.08	+3	-3

*Ear depth estimate based upon the descriptive statement that the subject's ear was "just under the surface of the water".

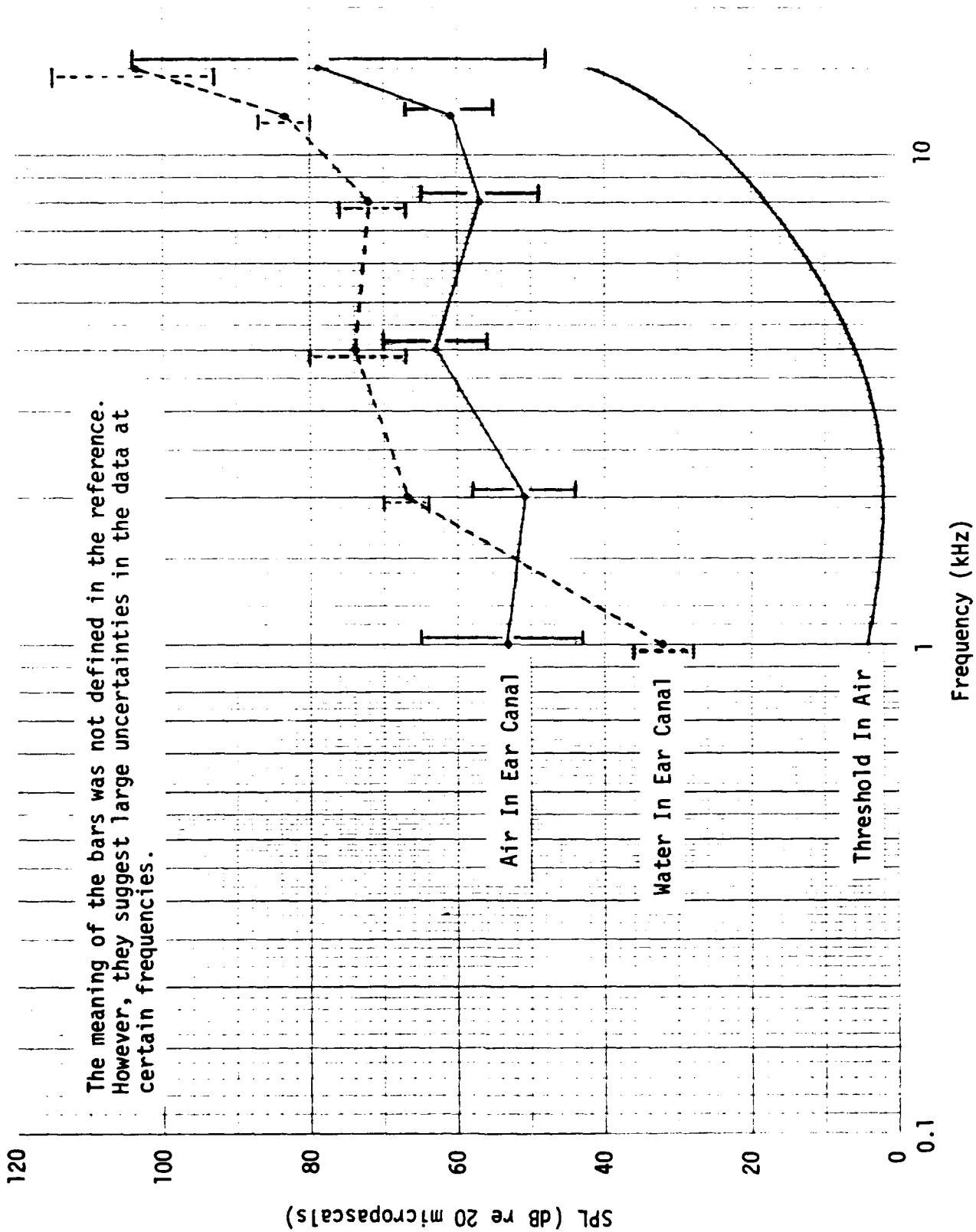


Figure 5-5
 Reysenbach de Haan's measurements of underwater thresholds of audibility for the conditions of air or water in the auditory canal, and his in-air reference threshold curve. The in-air reference curve appears to be similar to Sivian's (1933) monaural MAP curve with an adjustment for binaural listening. (After Reysenbach de Haan, 1956.)

In Figure 5-6 we have shown Reysenbach de Haan's threshold data adjusted by the total correction required (last column of Table 5-2) to account for the LLoyd mirror effect and the 6 dB bias. We have also replaced his "MAF curve" with the binaural MAF curve (0° incidence) from Killion (1978), which is based upon ISO R226-1961(E) but with Killion's low-frequency correction. The latter curve agrees reasonably well with Sivian and White's MAF data. (Their 1933 paper was one of the four research references used in the ISO recommendation of 1961.) At the lower end of the frequency range, we see that the differences between the underwater and in-air thresholds could be significantly less than those indicated by Reysenbach de Haan's original data. At the high-frequency end of the scale, the differences could actually be greater because of the lower sound pressure level values of the in-air MAF reference curve. The adjustments to Reysenbach de Haan's data cannot be considered to be exact since we do not know the subject's actual ear depth or how well it was controlled, nor do we know the condition of the water surface. These sample corrections are merely intended to illustrate the possible magnitudes of uncertainty in the experiment.

The assumption of a "smooth" pool surface is probably reasonably valid for the frequencies (wavelengths) used. Urick (1983, page 129) indicates that, if the Rayleigh parameter $R \ll 1$, the surface is primarily a coherent reflector (acoustically "smooth"). R is given by

$$R = kH\sin\theta$$

where

k = wave number, $2\pi/\lambda$

λ = wave length

H = rms wave height (crest to trough)

θ = grazing angle

For a wave height of 2 inches, which is a reasonable value for a "large pool" surface on a good-weather day, and a grazing angle of about 7° ($\arctan 3 \text{ m}/25 \text{ m}$), the following Rayleigh parameter values are calculated:

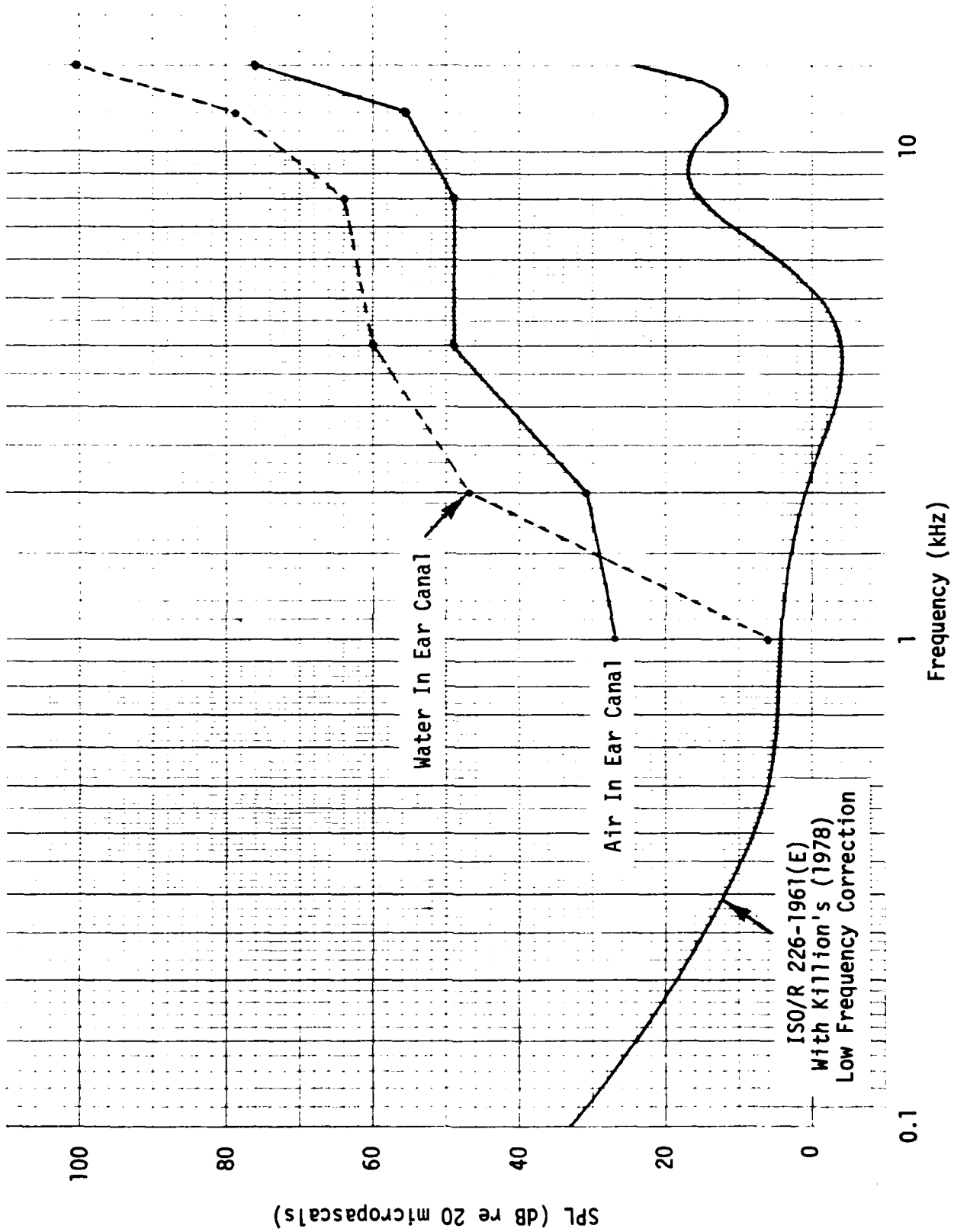


Figure 5-6

Reysenbach de Haan's underwater threshold data adjusted for the Lloyd mirror effect and corrected for the false assumption of 6 dB sound pressure doubling. Reysenbach

Freq (kHz)	λ (m)	R
1	1.5	0.026
2	0.75	0.052
4	0.375	0.104
8	0.1875	0.207
12	0.125	0.311
15	0.1	0.389

The values are all less than unity with particularly low values at the lower frequencies where we have made the larger corrections to Reysenbach de Haan's data.

Other uncertainties in the experiment include the lack of reporting of audiometric data for the three subjects (reported as having "normal hearing"), the unknown level of ambient noise in the water, and the effects of sound refraction (acoustic ray bending) over the 25 m distance between the source and the subject. The latter effect could slightly change the spreading loss assumption employed in the analysis. Although Reysenbach de Haan indicated that reflections "on the side of the pressure meter were likewise taken into account," there was no description of how this was done. This could be another *significant* source of error if not handled properly because of the effects of constructive and destructive interference between direct and reflected sound in the vicinity of his "pontoon." Direct measurements of the sound pressure levels *at the subject's head position* are really necessary in these kinds of experiments.

5.5 Hamilton (1957)

Hamilton conducted an experiment which corrected certain important deficiencies of previous work. Audiometric measurements were made for the four subjects used in the experiment and the data (for each diver's better ear) were presented in his paper. A calibration hydrophone was used to measure the actual sound pressure levels at the position the divers' heads would occupy. The tests were conducted in a fresh water lake from an anchored barge in 30 ft of water. "The location of the barge was chosen to minimize reflections and standing wave patterns." Ambient noise (masking) was thought not to be a problem because "critical band noise levels in the water were from 15 to 20 db below the thresholds obtained." When illustrating Sivian and White's (1933) free-field data in air for comparison purposes, Hamilton used the proper MAF curve (although slightly

smoothed at the high-frequency end). In principle, *this was a good experiment and the data should be reliable* assuming that all equipment was adequately calibrated and functioning properly.

Hamilton's experimental setup is shown in Figure 5-7. The four subjects used in the experiment were experienced divers from the U.S. Navy Underwater Demolitions Unit 1 and "had normal or better hearing in air." They were tested in pairs. The divers wore full rubber dry suits, aqualungs, face masks, but no hoods. The calibration hydrophone was placed "midway between the positions the divers' heads would occupy," and also was moved to the head positions with no change in sound levels (it is not known if this latter step was done at all frequencies). Tones of 250, 500, 1000, 2000, and 4000 Hz were employed for the threshold measurements.

The sound source was positioned 1 m away from the divers' heads at a depth of 4 m. Reflections would occur from the water surface at the location of the barge well, and conceivably from the barge structure and the lake bottom which was about 5 m below the divers. Some standing wave conditions would probably exist but would not be a serious problem with proper monitoring of the sound field. If the lake bottom was absorptive (e.g., mud), then the bottom reflection as well as multiple reflections (surface-bottom or bottom-surface, etc.) would be suppressed. The sound pressure level at the divers position associated with a single surface reflection at the location of the barge well would be 18 dB lower than the direct path signal because of the relative nearness of the source to the divers and the remoteness of the reflecting surface. The surface reflection therefore would most likely not be a problem. A flat barge bottom (off to the sides of the well) would not direct reflected sound toward the divers' positions; however, the possibility might exist of a "corner reflection" directed toward the divers and occurring in the vicinity of the intersection of the lake surface and the vertical walls of the barge well. This would also be a low-level signal.

The divers attempted to insure pressure equalization of their ears, and they held their breath during actual measurements to minimize the noise of exhaust bubbles. Twenty or more runs (ascending and descending sound levels) were made at each frequency. The repeatability of the measurements seemed reasonably good. "The greatest difference between the average threshold of the poorest and the best subject at any frequency was 6 db. The standard deviation of all tests ranged from 3.5 to 6 db at various frequencies."

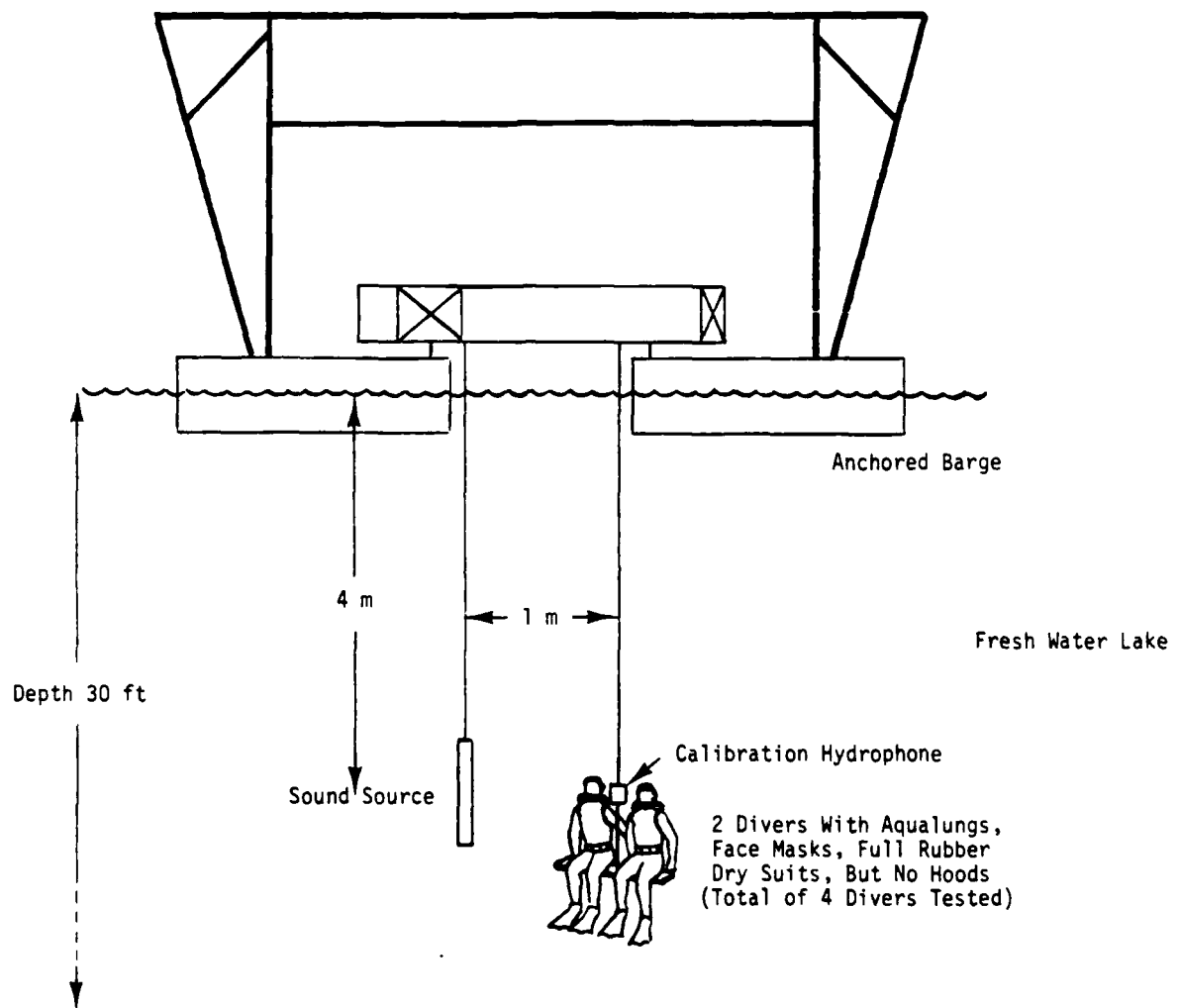


Figure 5-7

Hamilton's experimental setup for determining underwater thresholds of audibility.
(After Hamilton, 1957.)

Hamilton indicated that he did not attempt to flush the ear canals to eliminate air pockets "... because of objections from the medical officer" It is probable that some air remained trapped in the canals which is common in normal diving operations.

Hamilton's audiometric data which are shown in the upper part of Figure 5-8 were obtained in the period of time when the 1951 audiometric standards were in effect (ASA Z24.5-1951). In the lower part of the figure we have corrected these data to reflect the changes brought about by the ISO Recommendation 389-1964 (also ANSI S3.6-1969). As discussed elsewhere in this report, the MAPC values given in these two sets of standards differ by amounts ranging from 6 to 15 dB depending upon frequency. These corrections are being made to put all data into a common frame of reference reflecting the current standards.

Hamilton's underwater threshold data are shown in the upper part of Figure 5-9 along with a curve representing the mean MAF for the four divers used in the experiment. This mean in-air MAF curve was obtained by adding (or subtracting as appropriate) the corrected audiometric hearing levels to the free-field binaural MAF curve (0° incidence) of Killion (1978). The lower graph in this figure shows the differences between underwater and in-air thresholds based upon these adjustments. We see that the differences range from 31 to 59 dB.

5.6 Wainwright (1958)

Wainwright of the U.S. Navy Underwater Sound Laboratory, New London, Connecticut, conducted underwater audibility threshold measurements on two subjects in a "fresh-water field station at Dodge Pond" from a barge moored in 50 ft of water depth. Tones of 125, 250, 500, 1000, 2000, and 4000 Hz were projected from a transducer positioned 6 ft in front of the diver's head and at a depth of 10 ft. Each subject stood on a frame as shown in Figure 5-10 and wore closed-circuit SCUBA but no rubber suits. The closed-circuit equipment was selected to eliminate the problem of exhaust bubble noise with open-circuit SCUBA. (Other investigators using open-circuit SCUBA have had their divers hold their breath while taking data in an effort to control this noise source.) Wainwright indicated that "prior to the tests, measurements which were made on the closed-circuit SCUBA indicated that the noise of these devices was well below that of the threshold of hearing under water." However, Smith (1969) has commented that

"Closed circuit SCUBA, while not as noisy as open circuit SCUBA, is nevertheless much noisier than is normal

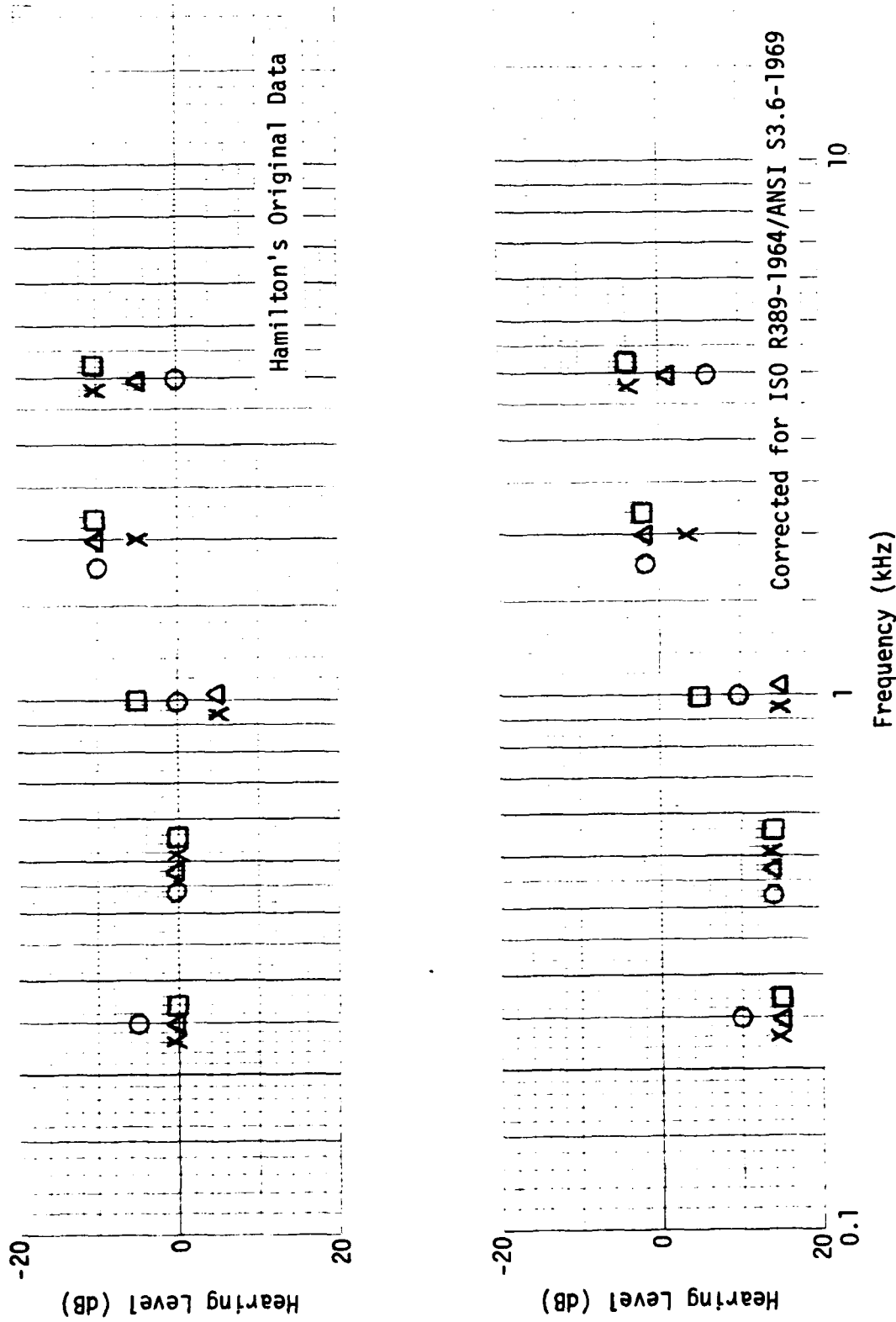


Figure 5-8

Upper graph - Hamilton's original audiometric data for the better ear of each of 4 subjects. (After Hamilton, 1957.) Lower graph - Hamilton's data corrected for revised audiometric standards of ISO R389-1964/ANSI S3.6-1969.

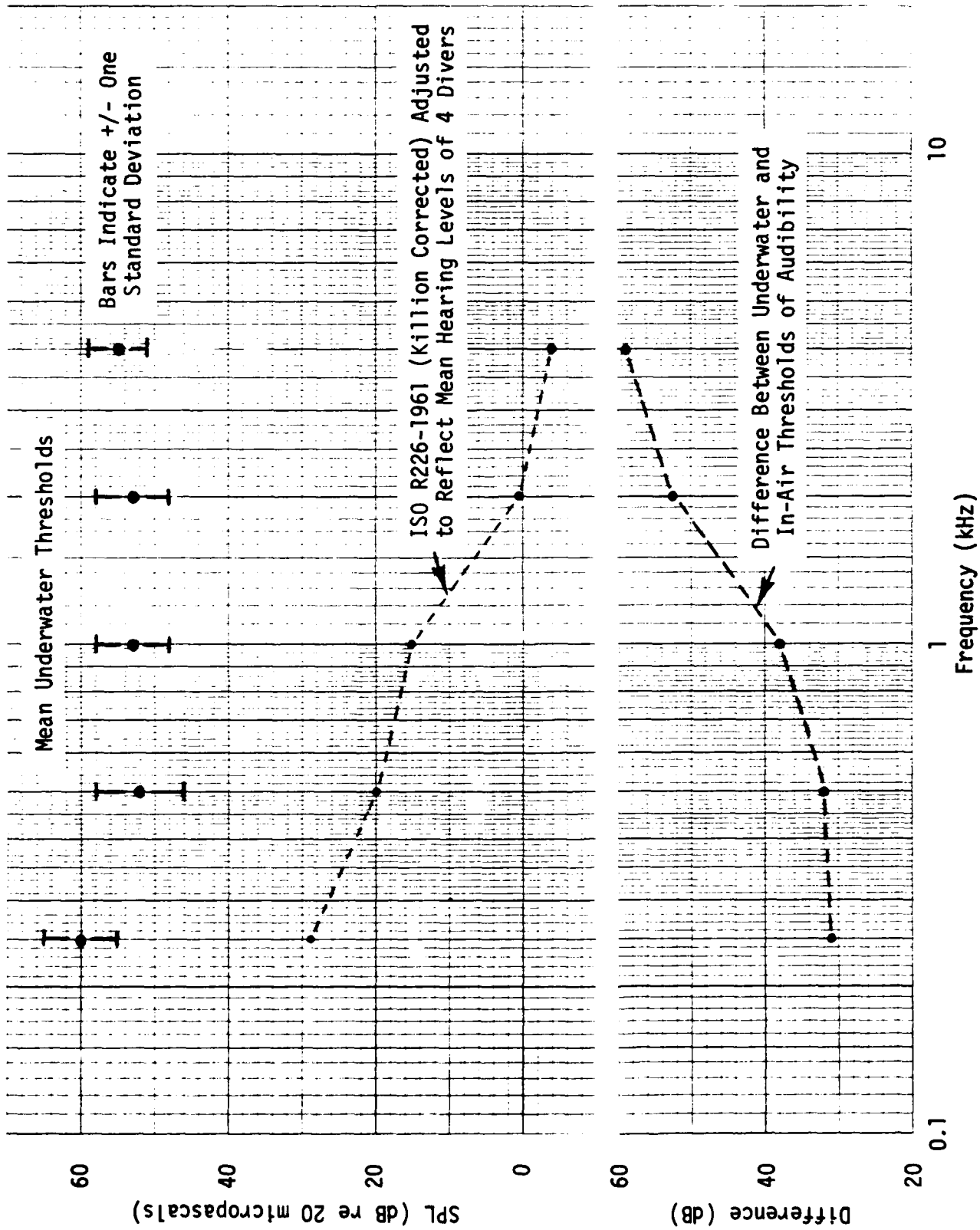


Figure 5-9

Upper graph - Hamilton's underwater threshold data compared with average binaural minimum audible field in air for specific sample of 4 divers. (Underwater data from Hamilton, 1957.) Lower graph - difference between underwater and in-air thresholds of audibility.

breathing in free air. The diver hears venting and flow noises every time he inhales or exhales or, depending on the type of closed circuit SCUBA in use, cycling noises due to the passage of air from canisters to breathing bags. These noises are not heard by the diver through the water but by "Tubal" conduction--through the mouth and nose and the Eustachian tube. Very little of this noise is radiated into the water. These noises subside somewhat, or even completely, in non-automatic systems, if the diver holds his breath, but apparently Wainwright's Ss did not do so."

The underwater projector used in this experiment "was calibrated and energized with signals of known level" There is no indication of the use of a reference hydrophone to measure the sound pressures at the diver's head position. Reflections from the surface and bottom of the pond, from the barge structure, or from equipment worn by the diver could interfere with the direct sound path signals producing reinforcement or cancellation effects and thus creating uncertainty as to actual sound levels.

Wainwright obtained the assistance of Dr. Donald Harris of the U.S. Naval Medical Research Laboratory to measure in-air "minimum audible sound pressure" for his two subjects. "These measurements were then converted to minimum audible fields" using Sivian's (1933) data. The results, averaged for the two subjects, are shown in Figure 5-11 in terms of intensity levels. These data seem to be somewhat abnormal. The author has stated that "the maximum difference in hearing acuity between the two (subjects) was 4 db at 4 Kc. Below this frequency, the deviation was less than 2 db." Therefore, both subjects would have to be abnormal by similar amounts. A representative curve for *normal* hearing (Killion, 1978), converted to intensity levels from sound pressure levels, has been added in Figure 5-11 for comparison purposes. We see that there are significant departures from the normal curve particularly at the lower and higher frequencies where the differences are about 34 dB (250 Hz) and 38 dB (4000 Hz) respectively.

These data must be considered suspect since it is improbable (although possible) that the two subjects would have essentially the same abnormalities; i.e., 2-4 dB differences or less over the entire frequency range employed. It is not clear what the author meant by his measurement of "minimum audible sound pressure" in air or how the measurements were converted to MAF values. These details were not provided. Were the basic measurements merely obtained by audiometry? Were the hearing levels so obtained merely added to or subtracted from one of Sivian's curves (preferably his

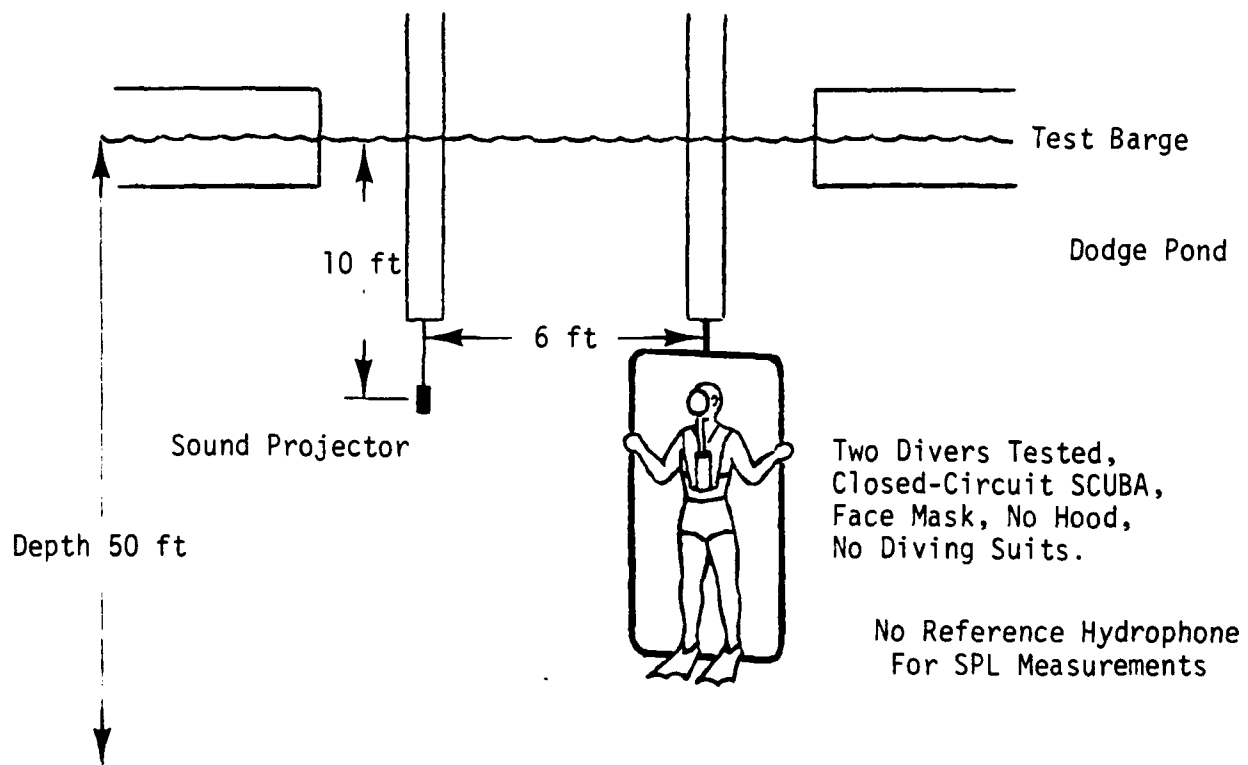


Figure 5-10

Wainwright's experimental setup for determining underwater thresholds of audibility.
(After Wainwright, 1958.)

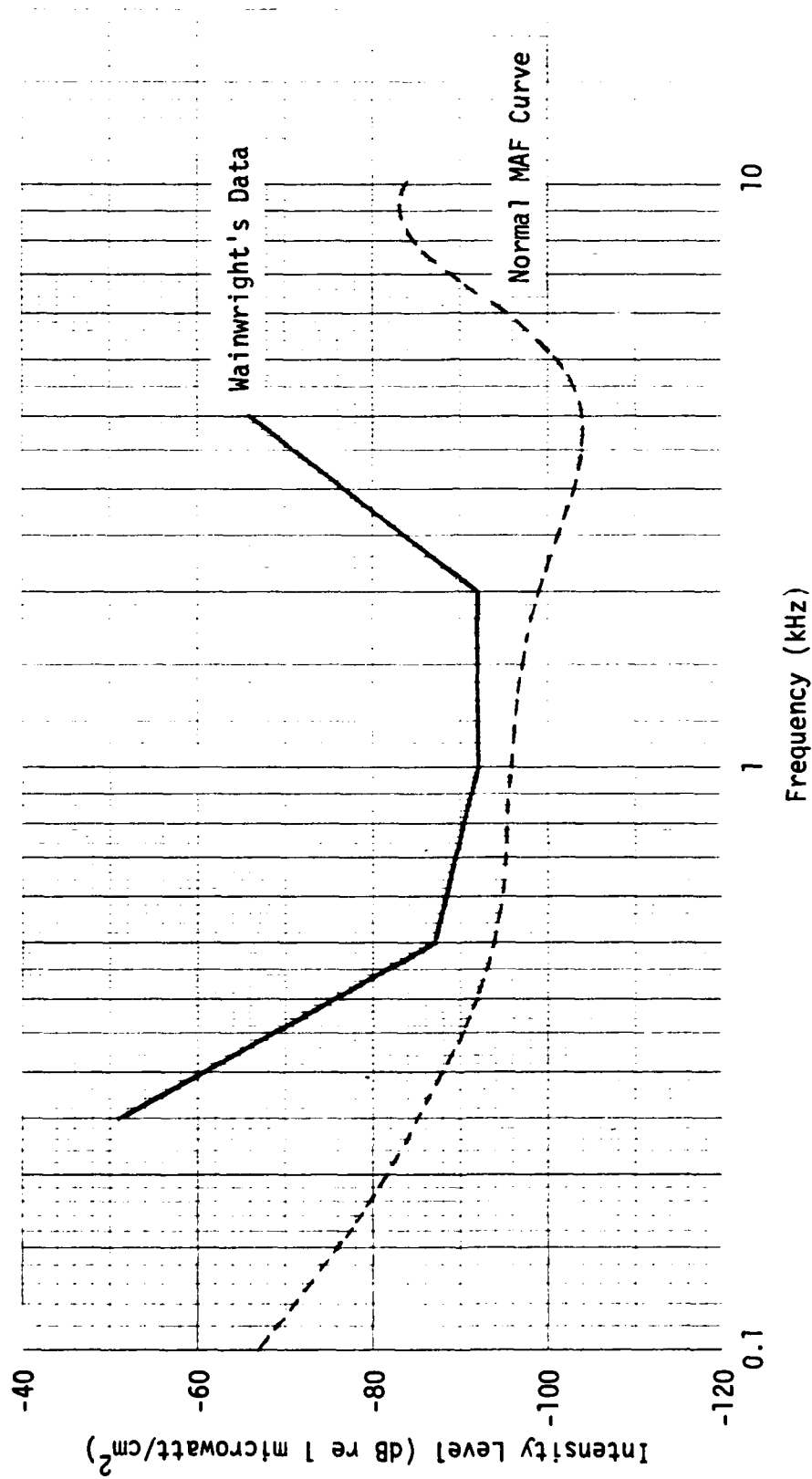


Figure 5-11

Wainwright's average in-air MAF data for 2 subjects compared with a standard binaural MAF curve for otologically normal persons in the age group 18 through 25 years. (After Wainwright, 1958. Normal MAF curve from Killion, 1978.)

binaural MAF curve), converted from sound pressure levels to intensity levels, and presented in the article as the data of Figure 5-11? Was a mistake made in this process causing the anomalous results?

Smith (1969), in his discussion of Wainwright's experiment, indicated that both subjects "had depressed AC and BC hearing levels (Submarine Medical Center records) at 4 and 8 kHz." Harris (1973), in commenting on Wainwright's paper, indicated that "both divers had AC audiometric losses of about 25 dB at 4 kHz." Neither of these statements explain the large difference at 250 Hz. Further, if both AC (air conduction) and BC (bone conduction) hearing levels were depressed, suggesting sensorineural hearing losses, one might expect to see similar anomalous behavior in the underwater threshold data particularly at 250 and 4000 kHz. Such an effect is not obvious in Wainwright's underwater results which are presented in Figure 5-12. The use of subjects with significant sensorineural hearing losses would result in underwater thresholds of audibility that would be higher than those for normal young ears. The data therefore would probably not agree with data of other investigators using young divers with normal hearing.

In view of the uncertainties associated with the experiment, it is concluded that the results would not necessarily be representative of normal underwater thresholds of audibility.

5.7 Montague and Strickland (1961)

Montague and Strickland conducted two experiments on underwater hearing the results of which were reported in the same paper. The first involved measuring audibility thresholds underwater for divers with and without hoods, and the second determined the limits of tolerance of divers to a high intensity tone. The description and comments in this section will deal only with the first of these experiments.

The test setup was similar to that used by Hamilton (1957). Montague and Strickland, as well as Hamilton, were associated with the U.S. Navy Electronics Laboratory and they may have used the same lake and barge facility for the experiments. The audibility threshold tests were "conducted in a fresh-water lake from a securely anchored barge" and "the water depth below the barge was approximately 25 ft." (these statements are very similar to Hamilton's except his depth was 30 ft). Each diver was positioned 1 m in front of a projector as illustrated in Figure 5-13. The projector and diver's head were at 3.9 m depth. (Hamilton's corresponding numbers were 1 m separation and 4 m

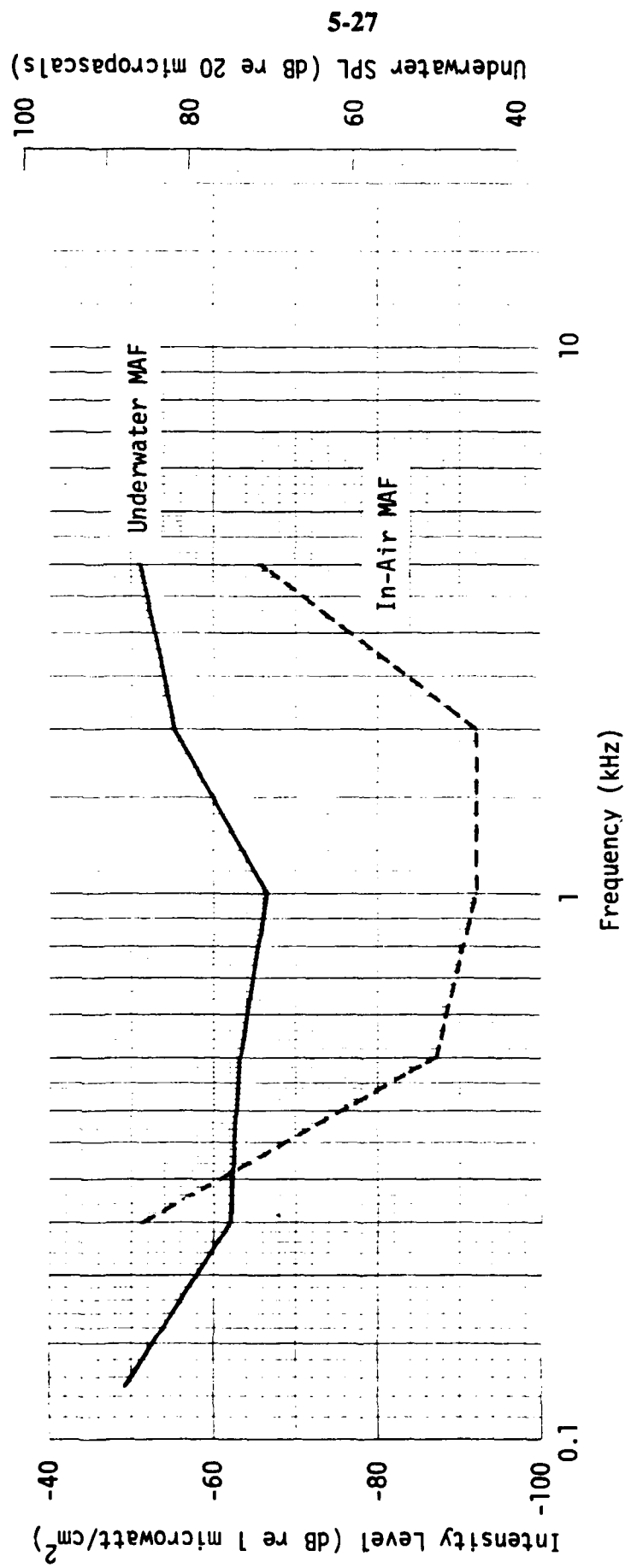


Figure 5-12

Wainwright's average underwater and in-air MAF data for 2 subjects. (After Wainwright, 1958.) Underwater data does not reflect anomalous behavior of in-air data at 250 and 4,000 Hz. Scale on right end of graph applies to underwater data only, with the conversion from intensity to SPL being based upon Wainwright's data.

depth.) A headrest, which is not shown in the figure, was provided to allow each diver to fix his head position.

Thresholds of audibility underwater were determined for seven divers using tones at frequencies of 250, 500, 1000, 1500, 2000, 3000, 4000, and 6000 Hz. The subjects used open-circuit SCUBA and wore face masks, hoods, and a full wet suit (3/16 in. Neoprene). Four of the divers were young UDU divers (ages 20, 21, 22, and 22) with "normal or better hearing" determined by audiometric measurements. The remaining three were scientist divers from NEL (ages 28, 28, and 41) who exhibited some degradation of hearing sensitivity at the higher frequencies. Unfortunately, the authors did not give the actual audiometric hearing levels for their subjects in the article but rather converted the data to sound pressure levels which were shown graphically. The method of performing this conversion was not described. Further, rather than illustrating a representative in-air binaural MAF curve for comparison with in-water measurements, they show Sivian and White's (1933) monaural MAP curve. The converted audiometric data as plotted are also referred to as "MAP thresholds". This confusion between binaural minimum audible field (MAF) data and monaural minimum audible pressure (at the eardrum) data makes it difficult to reconstruct from the article the actual hearing levels for the subjects. If one were to make a guess, one might suspect that the measured audiometric hearing levels were merely added (or subtracted, depending upon sign) to the MAP value at each frequency rather than to an appropriate MAF curve.

Montague and Strickland's underwater and in-air data for the four young UDU divers are shown in Figure 5-14. The in-air data generally fall slightly below the illustrated MAP curve which is consistent with their statement that the "UDU divers had normal or better hearing" The data points for the individual divers, however, would have been lower if the binaural MAF curve had been used as the proper reference. (As with Hamilton's experiment it should be noted that Montague and Strickland's work was done prior to the publication of ISO Recommendation 389-1964 and ANSI S3.6-1969 which changed the audiometric MAPC values by amounts ranging from 6 to 15 dB. These corrections would also have to be made to the audiometric data to make the values compatible with current standards.)

One of the important differences in Montague and Strickland's experiment versus Hamilton's was that no reference hydrophone was used to measure the sound pressure at the diver's head position. They relied instead on a "calibrated transducer" to project the sound. Unfortunately, signal interference and standing wave effects caused by reflections from the lake surface and bottom, from structures involved in the experiment such as the

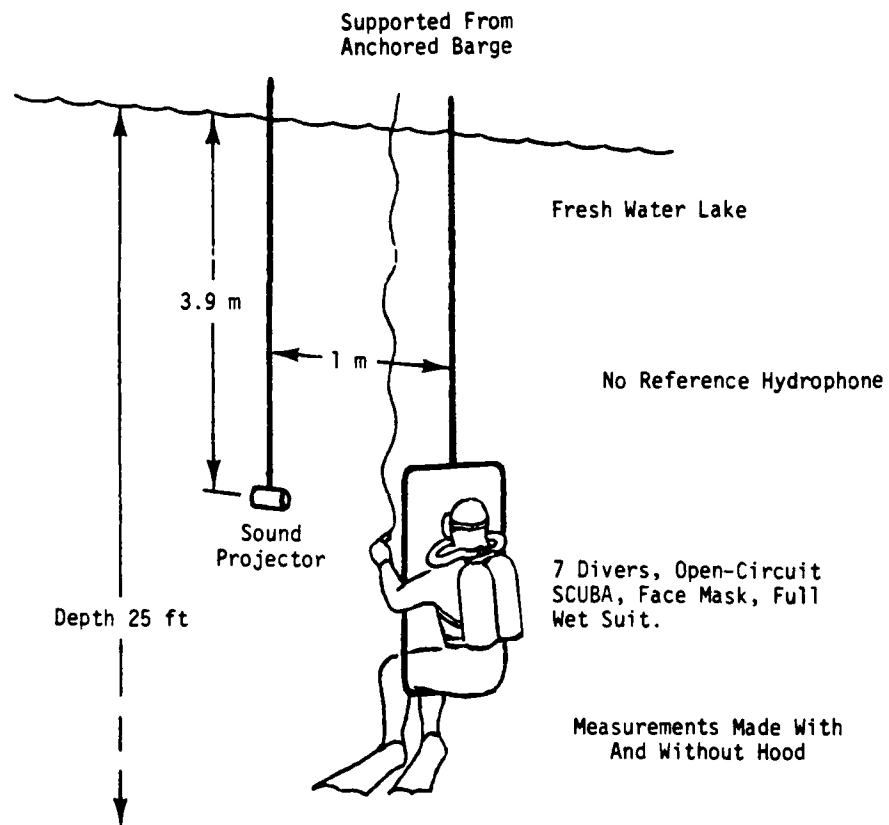


Figure 5-13

Experimental setup of Montague and Strickland for determining underwater thresholds of audibility. (After Montague and Strickland, 1961.)

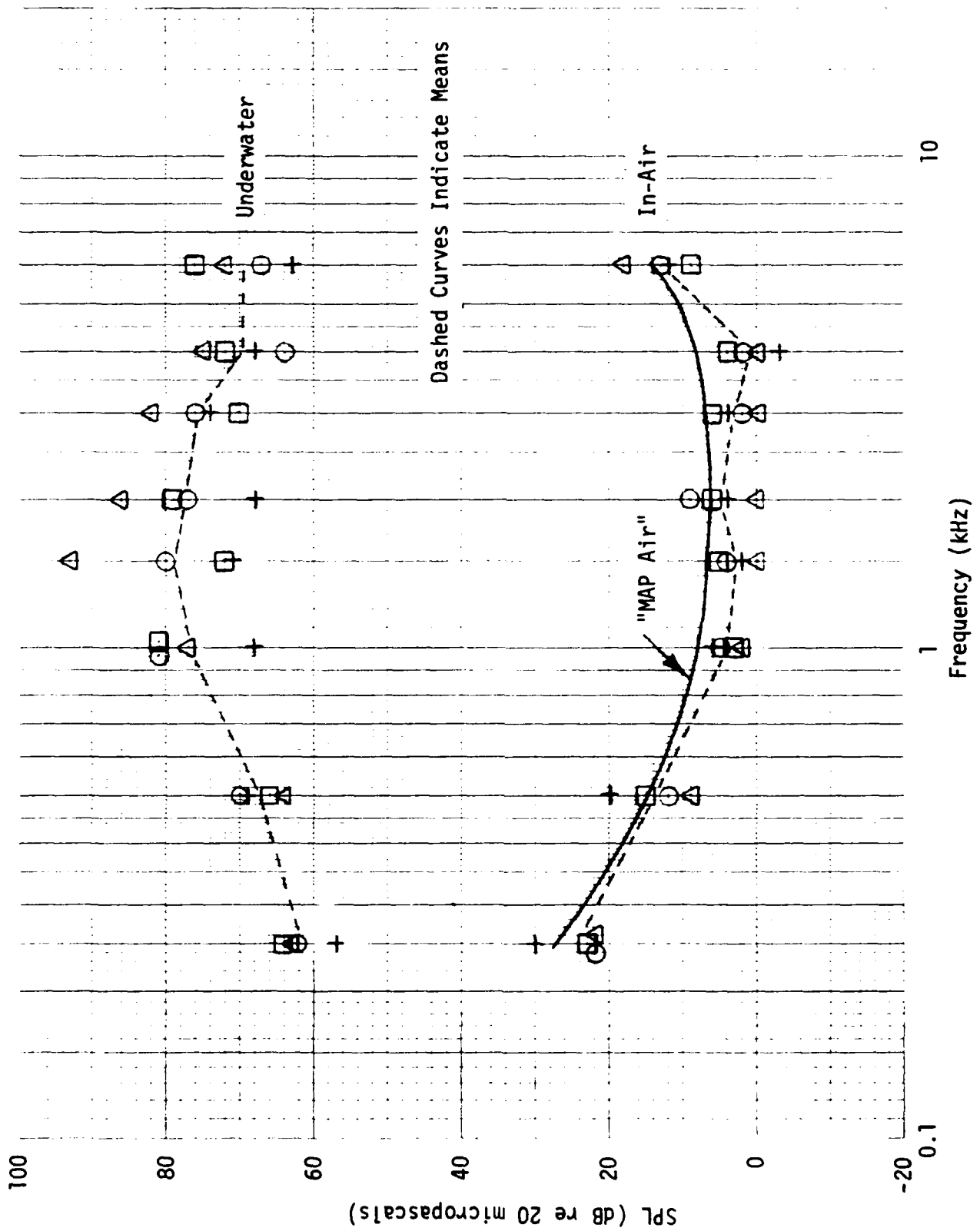


Figure 5-14

Underwater and in-air measurements of Montague and Strickland for 4 young UDU divers. (After Montague and Strickland, 1961.) Data for no-hood condition. Underwater thresholds are questionable because of a lack of underwater sound

barge and support frameworks, and from the diver's own equipment (e.g., wet suit--the diver's lap might provide a good reflecting surface) could make the predicted sound pressure values unreliable. In conducting the bare-headed measurements, the diver's hood was merely pushed back off the head. Reflections from that hood material bunched up on the back of the neck and head may have also contributed to sound pressure variations and therefore further uncertainty in the results. This latter possibility was suggested by Hamilton (1962) in a letter to the editor of JASA (also referenced by Smith, 1969). His subjects did not wear hoods. He also pointed out that different reflective/absorptive conditions may have existed because his "subjects wore *dry* suits rather than foam Neoprene wet suits" and he "tested two divers (seated about one foot apart, facing the sound source) simultaneously. There may have been some degree of sound reinforcement due to reflections."

Measurements were made at each frequency and for each diver first with the hood off (pushed back) and then with the hood on. The four UDU divers were tested using 3/16 in. hoods. The three NEL scientist divers were tested using 3/16, 1/8, and 1/4 in. hoods. The differences between the hood-off and hood-on data for all seven divers wearing the 3/16 in. hood are shown in Figure 5-15. The authors indicate that "very similar results were obtained with the three NEL divers wearing 1/8- and 1/4-in. hoods" (although no data were presented) and that "a shift in threshold of 20 db or more occurs at frequencies above 1000 cps when the diver wears the arctic hood." It is reasonably safe to assume that hoods will provide some attenuation and probably some protection from excessive noise. However, it must be pointed out that if the bunched up hood material caused perturbations of the sound field for the hood-off condition, then these measurements may be somewhat uncertain. Again, the need to monitor the sound pressures in the vicinity of the diver's head is essential in order to minimize the impact of such effects.

There was no mention of ambient noise conditions during the experiment. Since there was no monitoring hydrophone employed, there were probably no measurements made of the background noise.

In summary, we would conclude that the uncertainties in this experiment, particularly those related to knowledge of the actual sound field perturbations caused by nearby reflecting boundaries and objects, would negate the usefulness of the information in a data base aimed at *accurately* specifying the differences between underwater and in-air hearing.

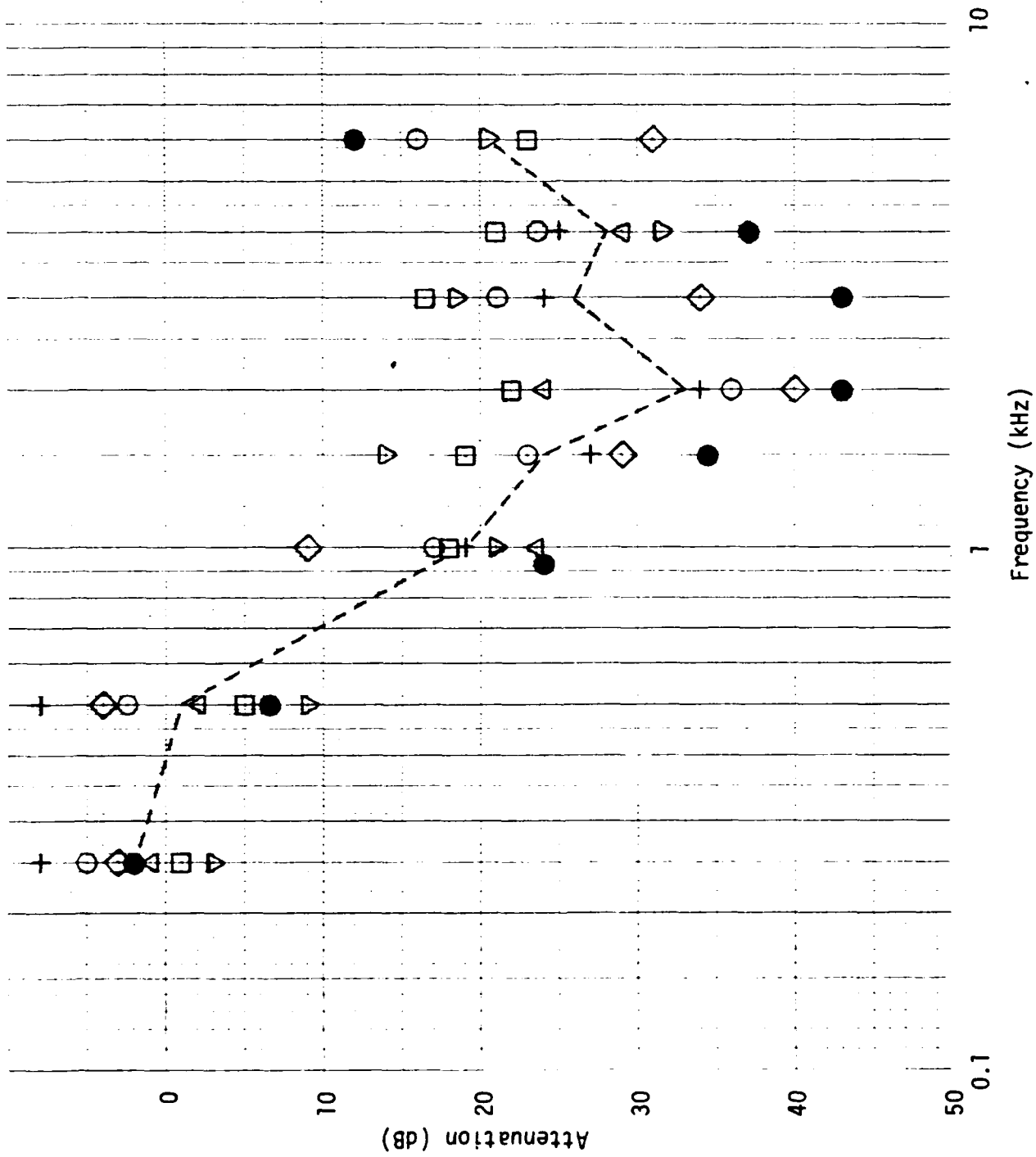


Figure 5-15

Montague and Strickland's measurements of sound attenuation provided by 3/16" foam Neoprene arctic hood. (after Montague and Strickland, 1961.) Note: missing data points for some subjects at certain frequencies were also missing in the original figure.

- 5.8 HOLLIEN, BRANDT, AND THOMPSON (1967)
HOLLIEN AND BRANDT (1969)
HOLLIEN, BRANDT, AND DOHERTY (1969)
HOLLIEN AND FEINSTEIN (1975)

A number of experiments on underwater hearing sensitivity were performed by Hollien of the Communications Sciences Laboratory (CSL), University of Florida, and other associates beginning in 1967. Because of similarities in the test facilities and instrumentation employed in these experiments, they will be discussed as a group. It is also possible, if not likely, that many of the same subjects were used in the various tests which would bias the results toward the hearing characteristics of that particular sample.

All of the experiments were conducted at the Bugg Spring test facility of the Naval Research Laboratory. The facility is located in the middle of the State of Florida. This is a pool approximately circular in shape with a diameter of about 400 ft. The walls of the pool are nearly vertical and drop to a depth of about 175 ft. A large barge is moored over the deepest part of the spring with the mooring lines running to points on the shore. A Diver Communication Research System (DICORS) which is "an open-framework diving cage constructed of polyvinyl chloride tubing" supported the subjects and was lowered through the well of the barge to the desired depths. DICORS is shown in Figure 5-16.

The instrumentation arrangement is illustrated in Figure 5-17 and was the same for all experiments except that the earphones were only used in the first experiment. (In-air measurements were made by conventional audiometric techniques in subsequent experiments. This subject will be discussed later.)

Each diver was positioned 1 m from the sound projector and wore open-circuit SCUBA and a wet suit. Thresholds of audibility were measured using pulsed tones "gated ON and OFF with a period of 500 msec, a 50% duty cycle, and a 2.5-msec rise-fall time." The frequencies generally ranged from 125 to 8000 Hz. The sound pressures at or near the diver's head position were measured using a reference hydrophone. For safety reasons, a buddy diver (a possible sound reflector) stood on the DICORS frame during the first of the four experiments and synchronized his or her breathing pauses with those of the subject so that exhaust bubble noise would be minimized during the actual threshold measurements. (A "buddy" diver was not mentioned in subsequent tests although one may have been present.)



Figure 5-16

Diver Communication Research System (DICORS).

(From Hollien and Tolhurst, 1969.)

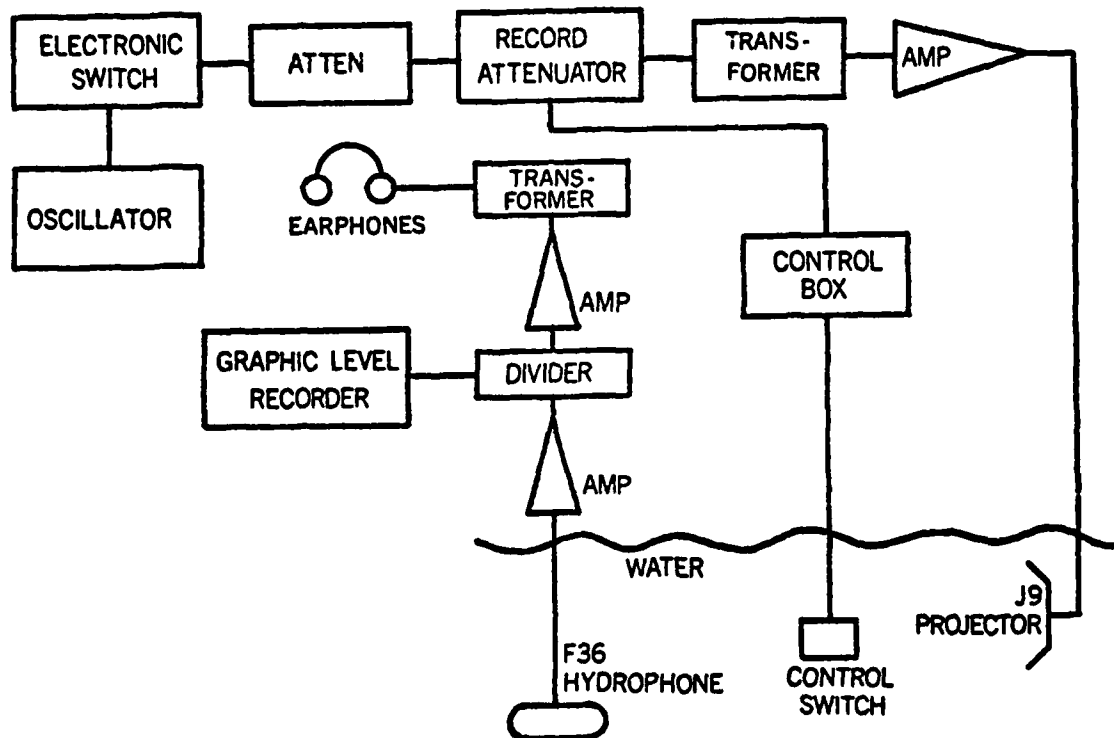


Figure 5-17

Block diagram of the stimulus generating equipment and response system.
 (From Hollien, Brandt, and Thompson, 1967.)

In the first experiment (1967), the underwater signals received at the reference hydrophone were routed to earphones for the purpose of threshold testing in air (but using underwater tones in the presence of underwater ambient noise). The levels so obtained were "higher than those usually obtained in a laboratory environment." and therefore additional measurements were made using a "sound treated room." The Bugg Spring data were found to be 10-15 dB higher at 1000 Hz and below than the thresholds obtained in the quiet room and these differences were attributed to both underwater background noise and "unavoidable fan noise of a power amplifier."

The underwater noise at Bugg Spring was described as "approximately that of sea-state zero and consists of wave slap, some hiss from the spring, and fish sounds." Assuming that the expression *sea-state zero noise* applies to the usually referred to typical deep-water ambient noise of the oceans, then the spectrum level for sea-state zero, at say 500 Hz, is about 21 dB re 20 μ Pa (Urick, 1967, page 168). Because of the masking effects of noise, a tone in order to be audible in the presence of a continuous spectrum must be above the spectrum level by an amount given by $10 \log_{10} BW_C$, where BW_C is the critical bandwidth of hearing. The critical bandwidth at 500 Hz, for example, is about 30 to 35 Hz (from Beranek, 1986, page 394), thus $10 \log_{10} BW_C$ would be about 15 dB. Therefore, the signal would have to be slightly above 21 plus 15 dB, or 36 dB SPL, to be detected at 500 Hz. This level is well above the normal binaural threshold of hearing in air (on the order of 6 dB at 500 Hz per Killion, 1978) so one might not expect to obtain valid in-air thresholds particularly at the lower frequencies using underwater signals in the presence of underwater noise at such levels. In the subsequent experiments by the CSL investigators, conventional audiometry was employed for in-air hearing assessment.

Table 5-3 is a summary of the four CSL investigations listing their purposes and key elements of each experiment. Note that in all of the experiments, 4 or 5 male divers and 2 or 3 female divers were used. They were probably members of the faculty and staff of CSL and the Navy's Mine Defense Laboratory (Panama City, Florida), as reported in the first paper of the group. This raises the possibility that at least some of the same subjects were used in all of the experiments and the results therefore would reflect their particular hearing characteristics. (This is not meant as a criticism but is merely meant to point out that the relatively close agreement in the thresholds obtained over the various experiments, as noted by the authors, would not be unexpected if the same subjects are used and if the same procedures and instrumentation are used.)

Table 5-3. Summary of CSL experiments on underwater hearing.

Reference	Purpose	Underwater Tone Frequencies	Subjects	In-air Hearing Assessment	Results
Hollien, Brandt, and Thompson (1967)	Underwater thresholds at 12 and 35 ft depths. No hoods.	125, 250, 500, 1000, 2000, 4000, 8000 Hz	5 male (27-40 years); 3 female; (25-28 years)	In-water signals to earphones, and also sound treated room	No statistically significant difference with depth
Hollien and Brandt (1969)	Underwater thresholds with air and with water in ear canals. No hoods, depth 12 ft.	125, 250, 1000, 2000, 8000 Hz	4 male 3 female	Rudmose automatic audiometer	No significant difference with air or water in canal
Hollien, Brandt, and Doherty (1969)	Underwater thresholds versus depth (35, 70, and 105 ft). No hoods.	125, 250, 1000, 2000, 8000 Hz	4 male 2 female	Rudmose automatic audiometer	No significant difference with depth
Hollien and Feinstein (1975)	Underwater thresholds at 30 ft depth; with no hood, with hood, and with hood having tubes to ear canal.	250, 500, 1000, 4000, 8000 Hz	4 male 3 female	None	Hood reduces sensitivity. Holes with tubes to ear canal makes no difference supporting bone conduction theory.

All experiments:

- Open-circuit SCUBA and wet suit
- Ears cleared (equalized pressure)
- Held breath when taking measurements
- Bugg Spring and DICORS
- Reference hydrophone used for calibration

In the first of the four "Hollien" experiments, underwater thresholds of audibility for bare-headed divers were measured at 35 ft depth for eight subjects, and at 12 and 35 ft for three subjects. The results are shown in Figures 5-18 and 5-19. There was little difference between the threshold curves for the two depths. This work was extended in the second experiment to include threshold measurements at 35, 70, and 105 ft. Again, there was little difference between the threshold values for the various depths, as shown in Figure 5-20. The authors concluded that "increases in ear depth from 12 feet.... to 105 feet.... have no effect upon free field underwater hearing thresholds in the frequency range between 125 and 8000 Hz."

The third Hollien experiment was conducted to determine the effect on underwater thresholds of air bubbles in the ear canals. Tests were run on seven bare-headed divers at 12 ft depth with air trapped in the canals and with the ears flushed with water to remove any trapped air. The results shown in Figure 5-21 revealed little difference in the thresholds for the two conditions.

The fourth and last experiment was intended to test the hypothesis that the mechanism for underwater hearing is primarily by bone conduction. Measurements were conducted for the three different conditions of bareheaded diving, diving with a hood, and diving with a hood modified with rubber tubes passing through the sides into the ear canals to allow in-water sound to enter and activate the ear drum. This experiment also provided information on the attenuation properties of a 3/16-in. hood (the possible hearing protection offered by hoods is discussed elsewhere in this report). The results of the experiment, Figure 5-22, showed significant differences between bare-headed thresholds and thresholds obtained with the conventional hood at frequencies of 1000 Hz and above. However, there was little difference in the threshold curves for the conditions of hooded divers and divers wearing the hoods with ear holes. The authors concluded therefore that the results "support the hypothesis that the middle ear does not play a prominent role in the process of human underwater hearing."

In-air sensitivity measurements were performed in the first three "Hollien" experiments. The fourth experiment was conducted for the purpose of comparing underwater hearing with and without hoods (including the hood with ear tubes) and therefore air conduction thresholds were not required and were not measured. In the first experiment, audiometric-type measurements were attempted using the underwater tones fed to ear-phones. Because of background noise problems, questionable data were obtained. Therefore, in-laboratory tests were also performed. A Rudmose automatic audiometer was used in the second and third experiments.

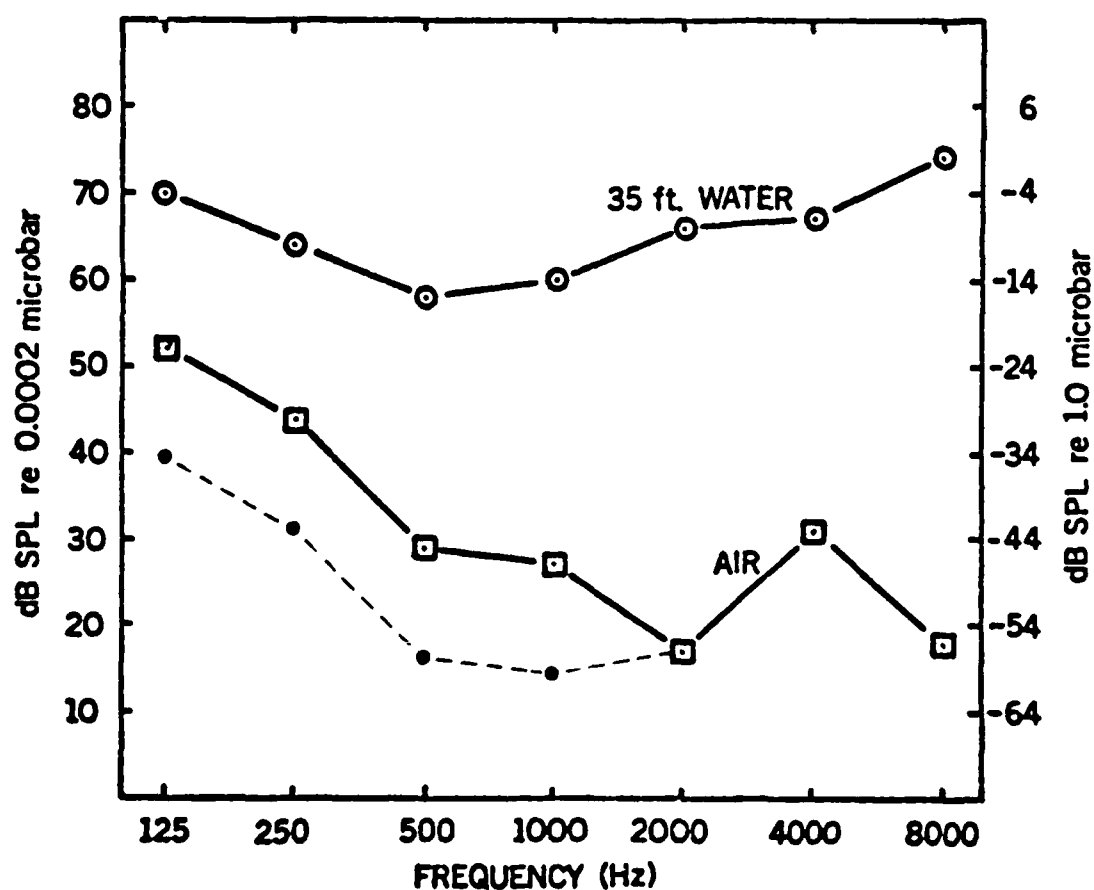


Figure 5-18

Mean threshold SPL in air and water (35-ft ear depth) as a function of frequency for eight listeners. (From Hollien, Brandt, and Thompson, 1967.) Dashed curve has been added and shows authors' recommended corrections.

Note: Because of ambient noise conditions and the method of measuring in-air thresholds using underwater signals routed to earphones in the first of the group of four experiments, the "air" data in this figure are questionable. The authors suggested subtracting 13 dB from the air conduction thresholds at 1000 Hz and below to be compatible with "sound treated room" data.

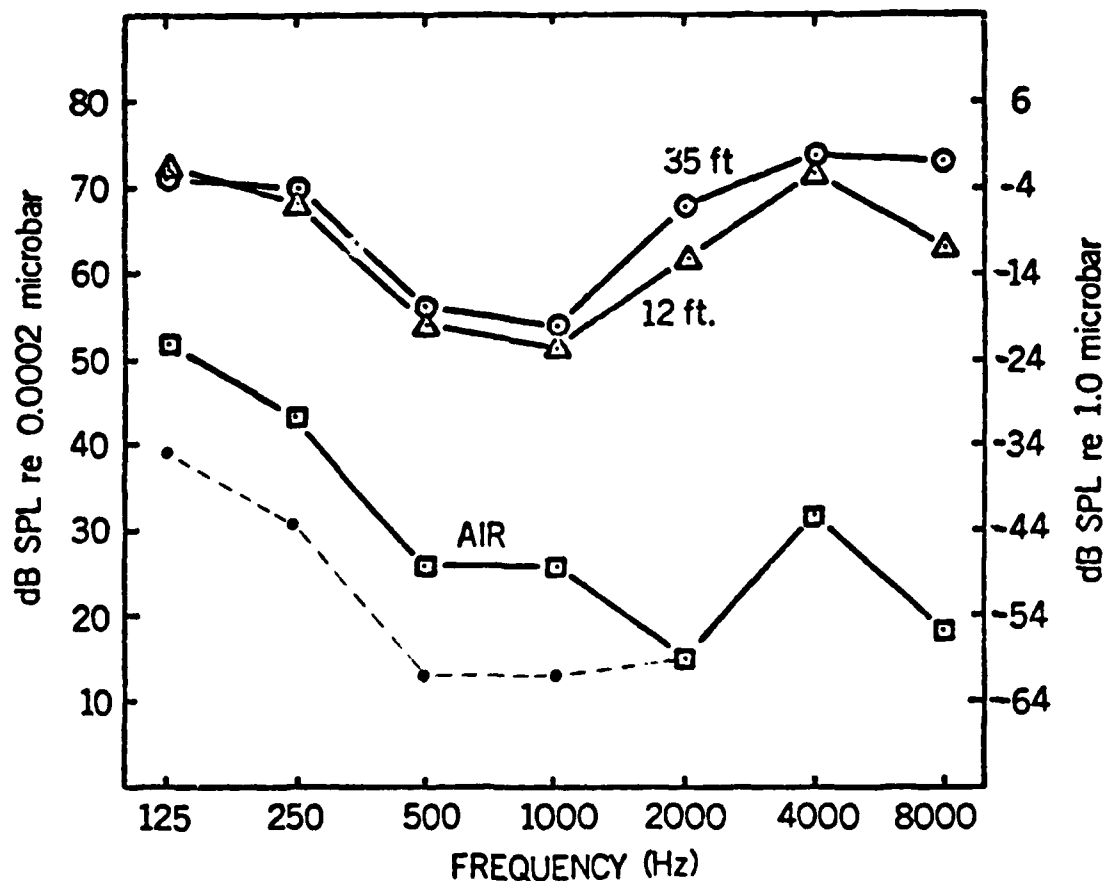


Figure 5-19

Mean threshold SPL in air and water (12 and 35-ft ear depth) as a function of frequency for three listeners. (From Hollien, Brandt, and Thompson, 1967.) Dashed curve has been added and shows authors' recommended corrections.

Note: Because of ambient noise conditions and the method of measuring in-air thresholds using underwater signals routed to earphones in the first of the group of four experiments, the "air" data in this figure are questionable. The authors suggested subtracting 13 dB from the air conduction thresholds at 1000 Hz and below to be compatible with "sound treated room" data.

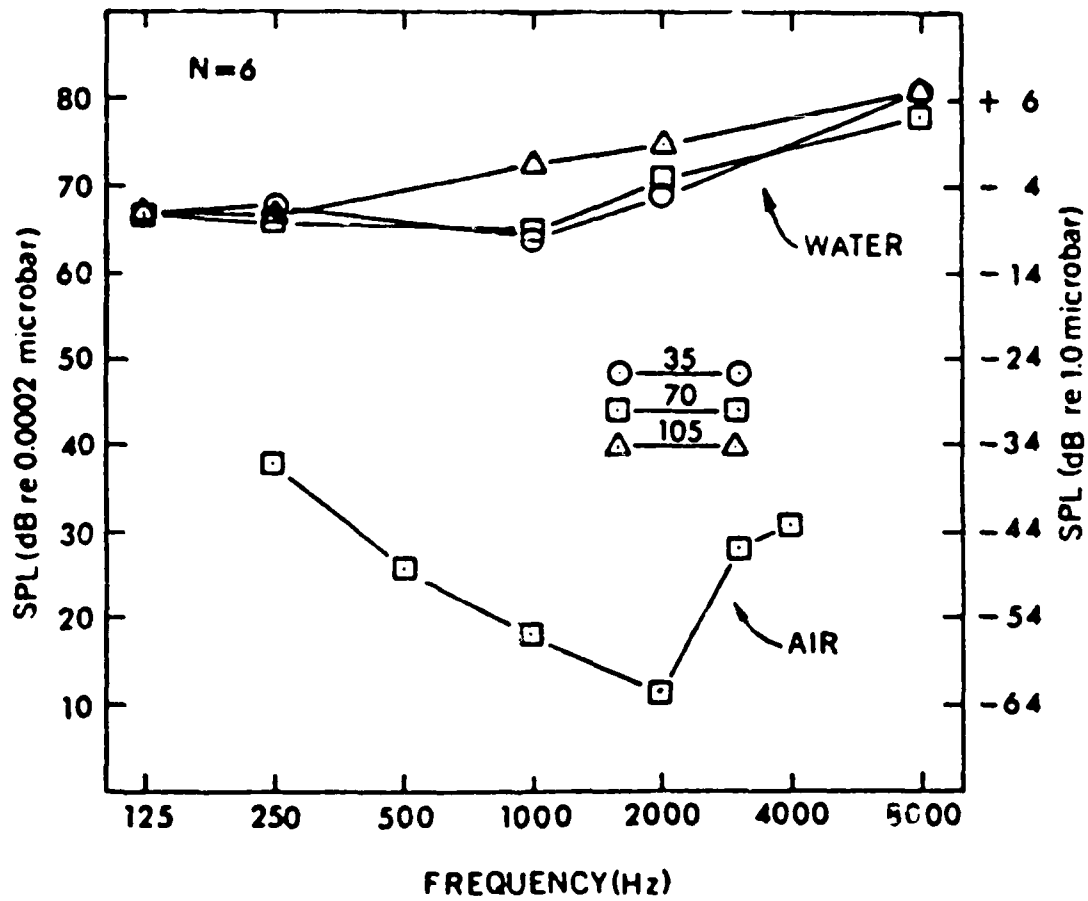


Figure 5-20

Mean threshold SPL as a function of test frequency in air and water at three depths. N = 6 diver/listeners. (From Hollien, Brandt, and Doherty, 1969.)

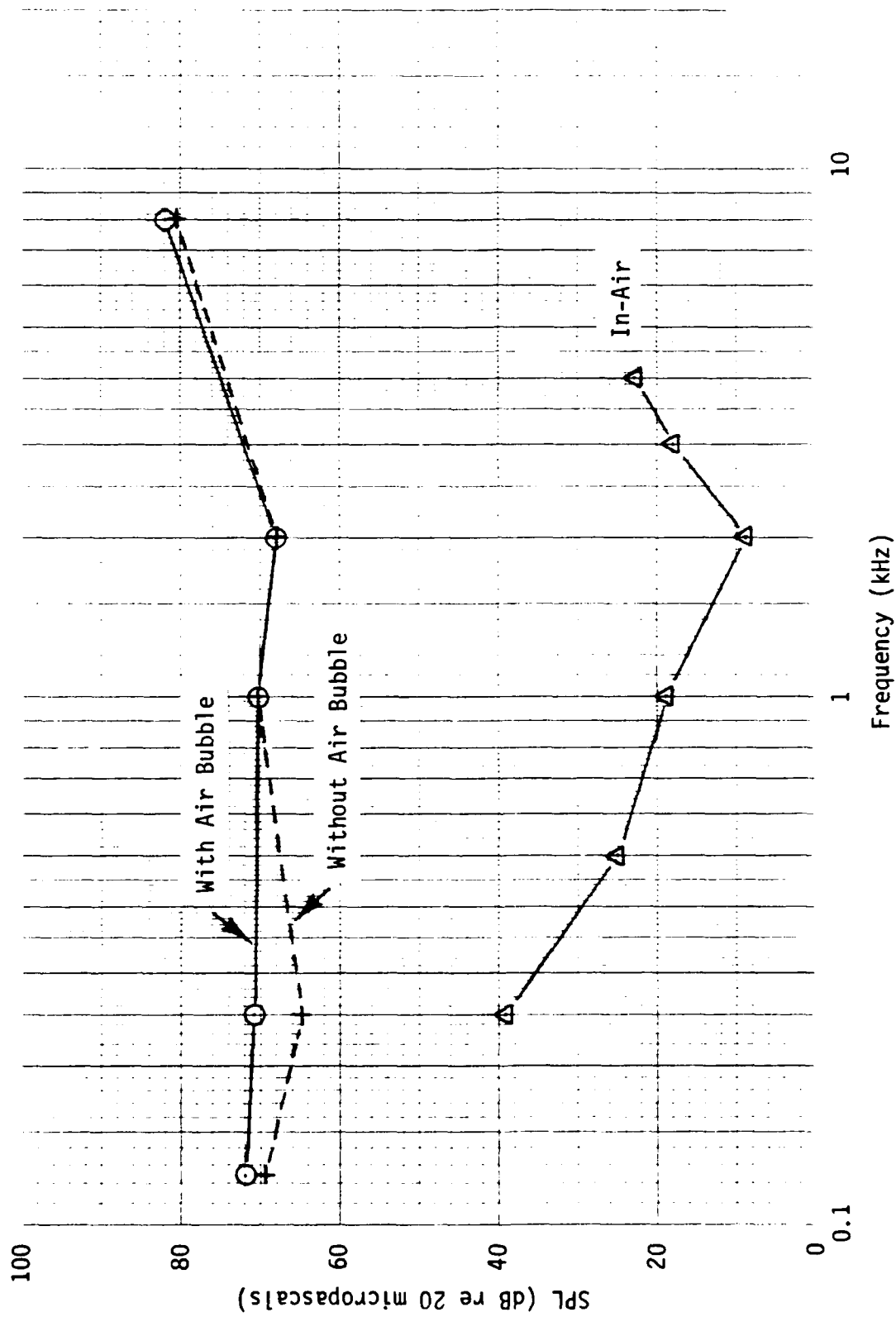


Figure 5-21

Hollien and Brandt's mean underwater thresholds with and without air bubbles in the ear canals compared with their determination of in-air thresholds. (After Hollien and Brandt, 1969.)

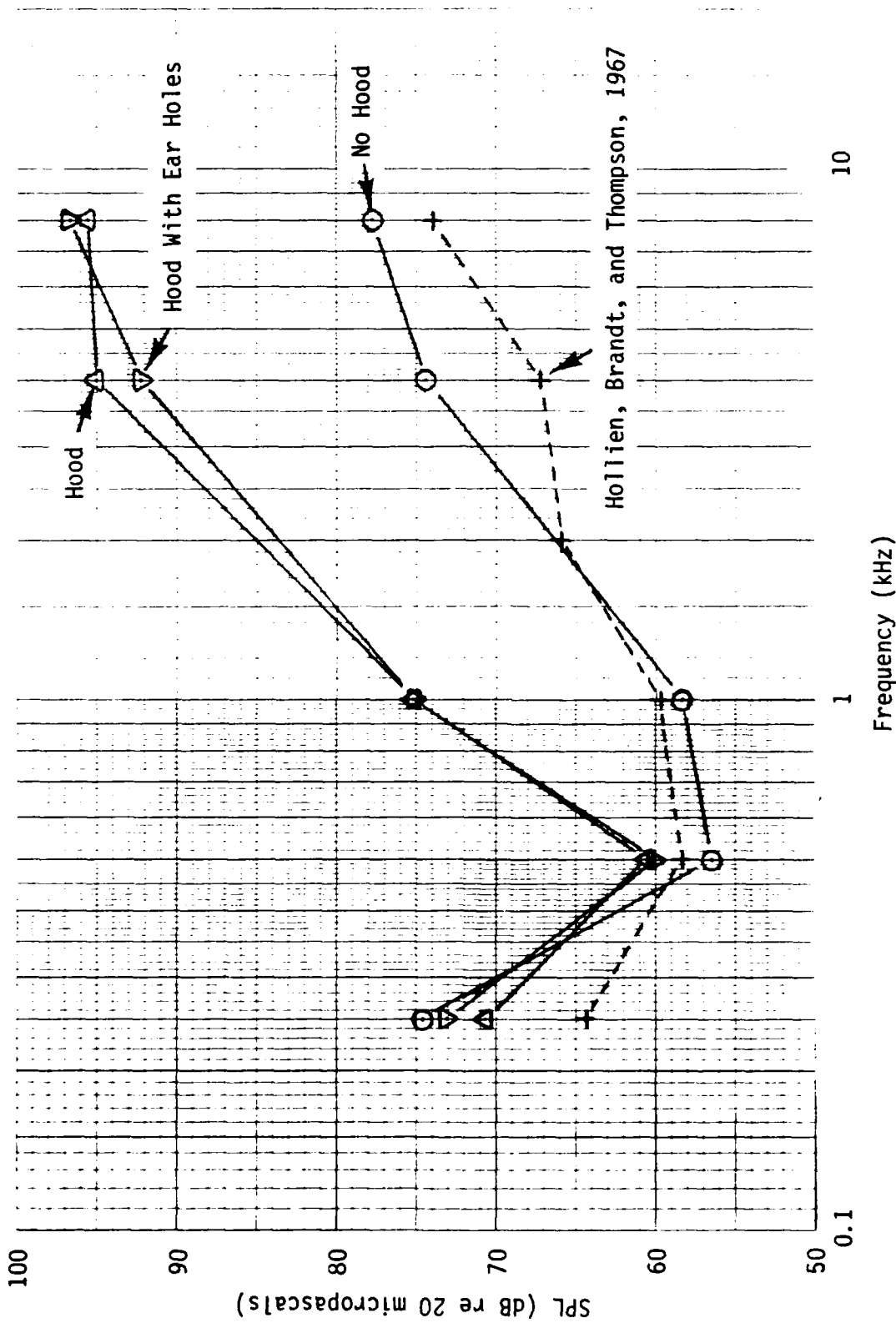


Figure 5-22

Mean thresholds of audibility for various head covering conditions, 7 subjects, 30-ft depth. (After Hollien and Feinstein, 1975.) Data shows the differences between hood and no-hood conditions, and indicates no significant differences between sensitivity for hood and hood-with-ear-holes conditions.

Unfortunately, hearing level data (relative to *audiometric-zero*) were not presented in any of the articles. Rather, the data were converted to in-air thresholds of audibility in terms of sound pressure level for comparison (in tabular and graphical form) to the underwater thresholds. The procedure for making these "conversions" was not described.

Figure 5-23 shows the underwater thresholds for the four experiments, the in-air thresholds for the first three experiments, and two representative binaural MAF curves for normal young ears--Sivian and White (1933) and Killion (1978)--which agree reasonably well.* We see that most of Hollien's in-air threshold data are well above either of the two reference curves for binaural MAF. This could mean that the subjects used in the experiments had, on the average, depressed hearing; or that the conversions from audiometric data to equivalent binaural MAF values were not valid. One might suspect the latter of these two reasons because, as Sivian and White (1933) pointed out, "It is well established that in the age range of 20 to 35 years for normal people, there is scarcely any aging effect for auditory acuity below 1000 c.p.s." In contrast, Hollien's AC data in Figure 5-23 is displaced from the normal MAF curves fairly uniformly throughout the range from 100 to 2000 Hz. (There is a greater departure at 3000 and 4000 Hz which could indeed indicate some hearing loss at these frequencies.)

As further evidence of a problem of converting audiometric to MAF data, it was pointed out in Hollien's first experiment that "water conduction-threshold SPL was measured by the method of minimum audible field (MAF). The air conduction-threshold SPL, on the other hand, was measured by the method of minimum audible pressure (MAP). No correction for the possible differences in SPL values resulting from the two methods was attempted." It is unclear what was meant by this statement, however, it suggests that there may have been some confusion between MAF (minimum audible field), MAP (minimum audible pressure at the eardrum), and MAPC (minimum audible pressure as measured by a standard earphone coupler). These terms have been discussed elsewhere

*The underwater threshold data for Hollien's first experiment are mean values for eight subjects at 35-ft depth. The data for the second experiment are overall means for seven subjects at 12-ft depth and for the two conditions of air or water in the ear canal. The data for the third experiment are overall means for six subjects and three depths - 35 ft, 70 ft, and 105 ft. The data for the fourth experiment are mean values for seven subjects at 30-ft depth.

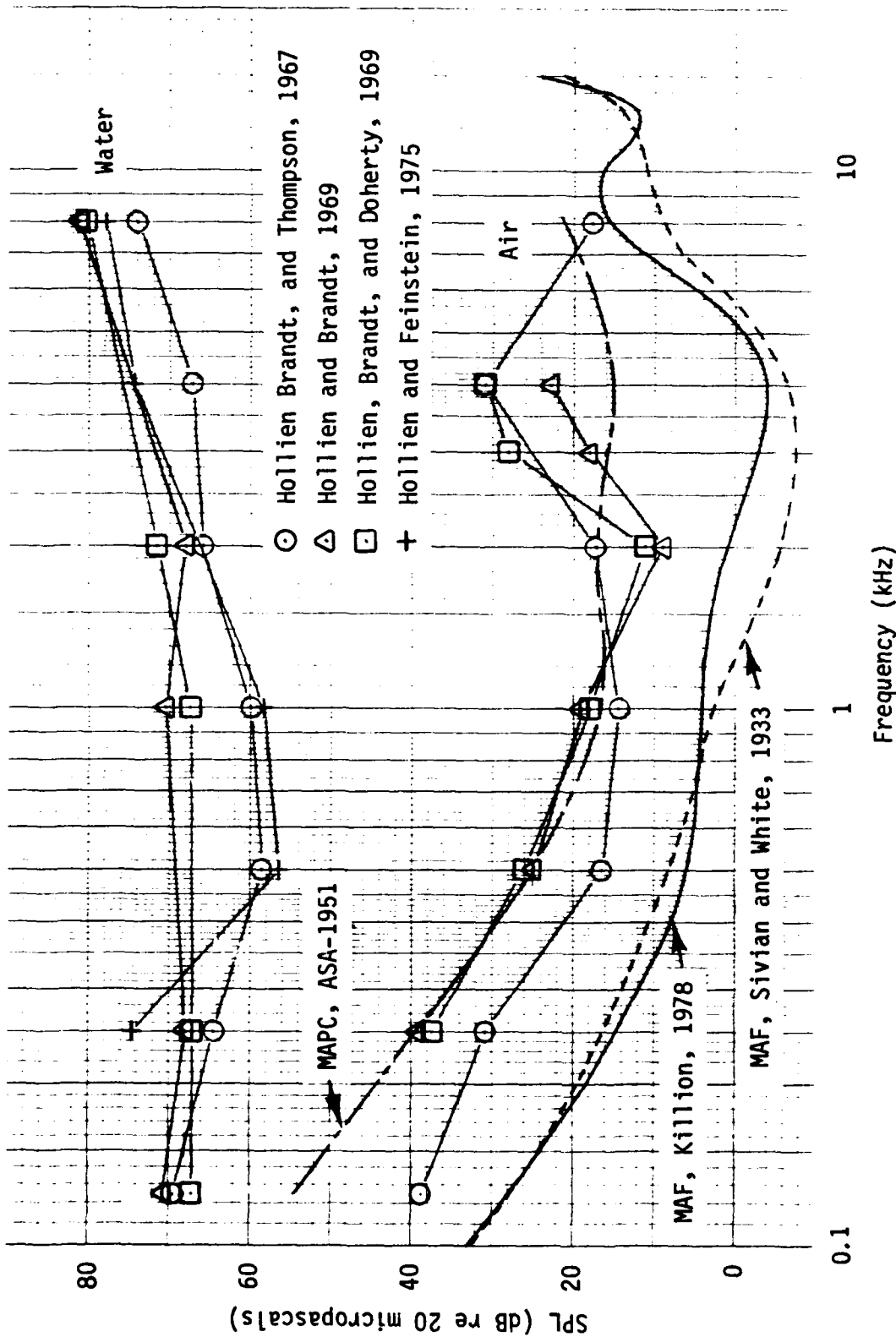


Figure 5-23

Hollien's determinations of underwater and in-air thresholds of audibility from four experiments; the in-air thresholds are compared with selected MAF and MAPC reference curves. (The data are from the references noted on the graph.) The MAF curves from Killion and from Sivian and White are in reasonable agreement and are representative of normal young adult binaural listening (0 degree azimuth). However, Hollien's in-air data appear to be distributed about the MAPC curve of ASA Z24.5-1951. (Note: the in-air data from Hollien's first experiment, circle symbol, were questionable at 1,000 Hz and below and have been adjusted by subtracting 13 dB in accordance with Hollien's own suggestion.)

in this report. A representative MAPC curve has also been included in Figure 5-23 and we see that Hollien's in-air data track much better with that curve than with the MAF curves.

Another uncertainty in the problem of evaluating the AC thresholds obtained in the Hollien experiments was the change in U.S. audiometric standards that was officially adopted on September 1, 1970, and which also has been discussed elsewhere in this report (ASA Z24.5-1951 versus ISO 389-1964 and ANSI S3.6-1969). The earlier MAPC Reference Values (1951) were 6 to 15 dB higher than the later (1970) values for the same earphone-coupler combination (see Table 4-2). If a subject exhibited a hearing level of zero dB at a given frequency under the old standards, he or she would exhibit a "poorer" hearing level under the newer standards by 6-15 dB (depending upon frequency) because the reference pressure values have been reduced and the audiometric level would have to be increased to be heard (assuming no actual hearing change). Three of the four "Hollien" experiments were definitely conducted prior to 1970 (publish dates of 1967, 1969, and 1969) and could have been using either the 1951 or 1964 audiometric standards. Although the fourth experiment may have been conducted prior to the publish date of 1975, AC threshold measurements were not necessary and were not included. Therefore the question of audiometric standards is not relevant to the last experiment. Hollien's audiometric data, therefore, might require adjustment to account for this change in standards in order to obtain more accurate estimates of the differences between underwater and in-air hearing.*

If Hollien's subjects, on the average, had "normal" hearing at frequencies of 1000 Hz and below (the mean age for the five males in the first experiment was 31.0 years and for the three females 26.3 years, therefore, significant lower frequency aging effects should not yet have occurred), then their AC thresholds when converted from audiometric data to free-field data should have been centered around the representative MAF curves of Figure 5-23. Instead they seem to be clustered in the vicinity of the MAPC reference values of 1951, at least from 250 to 2000 Hz. This latter observed correlation suggests that the conversion may have been improperly done being based upon MAPC rather than MAF data.

*It is bothersome that none of the authors during this era mentioned the confusion over audiometric standards and clarified in their articles which standards were being applied.

The question of what are the actual in-air thresholds of audibility for Hollien's subjects is fundamental to judging the validity of the underwater thresholds, as well as the differences between underwater and in-air thresholds, as being representative of "normal young ears." If they truly had depressed hearing in air, they would probably exhibit depressed hearing in water since sensorineural hearing losses are the most common and would be observed in both the air (AC) and underwater (BC) environments. If conductive hearing losses (i.e., via the tympanic route) were present in any of the subjects, then they would exhibit depressed in-air hearing but might not exhibit depressed underwater hearing because of normal bone conduction. (It is practically impossible to have "good" AC hearing and "bad" BC hearing.) However, neither conductive nor sensorineural losses of a significant nature would be expected in Hollien's selected samples because of their relatively young ages (assumed on the basis of the first experiment).

In conclusion, Hollien's data can be questioned on the basis of "non-normal" in-air thresholds of audibility. The underwater thresholds may be valid since the experiments appear to have been well-instrumented and well-controlled, but they will reflect the actual hearing sensitivities of the individual subjects.

One final point needs to be mentioned. In all of the four Hollien experiments, standard deviations associated with the spread of the mean threshold values over all subjects at each frequency were presented. (Each mean for each subject was calculated from several threshold determinations--e.g., 3 or 4 or more.) Table 5-4 gives the spread in the standard deviations and the average of the standard deviations for each experiment. There is a trend for the average standard deviations to be smaller for the in-air measurements (2.7 to 6.2 dB) than for the in-water measurements (6.2 to 11.7 dB); it is noted that the sample sizes were small for two of three in-air measurement sets (number of frequencies, $n=3$). Keeping in mind that in a normal distribution approximately two-thirds of the means for each set of measurements should fall within $\pm 1 \sigma$ of the overall mean, and conversely that one-third of the data should fall outside of $\pm 1 \sigma$, we see that the variability from subject to subject is quite large in these experiments. Smith (1969), whose experiments will be described next, conducted repeatability measurements of underwater thresholds on the same subjects over an extended period of time. He found the variability to be quite large even for a single subject. Large inter-subject or intra-subject variability significantly reduces the confidence in the estimate of the true means(s) for the overall population, particularly when sample sizes are small. Therefore, if large variability is typical, underwater threshold determinations could be considered to be unreliable unless sample sizes (number of subjects) are quite large.

Table 5-4. Standard deviation spread and average value for each of Hollien's four experiments.

<u>Experiment</u>	<u>Spread (dB)</u>	<u>Average σ (dB)</u>	<u>No. of Freq.</u>
<u>Water</u>			
1	9.82-2.97 = 6.85	6.17	7
2 (bubble)	11.1-5.5 = 5.6	8.0	5
(no bubble)	13.7-4.1 = 9.6	7.6	5
3 (35 ft)	14.0-5.6 = 8.4	8.0	5
(70 ft)	14.6-5.8 = 8.8	8.7	5
(105 ft)	14.4-8.4 = 6.0	11.7	5
5 (Bare Head)	8.28-6.55 = 1.73	7.37	5
(Hood)	11.39-7.90 = 3.49	9.50	5
(Hood with Holes)	10.43-7.55 = 2.88	9.08	5
<u>Air</u>			
1	11.18-3.11 = 8.07	6.21	7
2	3.5-2.2 = 1.3	2.7	3
3	7.3-2.5 = 4.8	4.4	3
4	----- None Taken -----		

5.9 Smith (1965) Smith (1969)

Smith of the U.S. Naval Submarine Medical Center in Groton, Connecticut, conducted an experiment circa 1964-1965 using eight breathholding men (swimmers wearing trunks--no SCUBA) in a small circular pool to obtain measurements of underwater hearing thresholds of audibility. Another series of experiments, reported in February 1969, was performed by Smith under better environmental conditions and consisted of: (1) measurements of thresholds of audibility underwater, (2) tests to determine the effect of pressure (depth) on the sound attenuation provided by divers' hoods, and (3) underwater threshold repeatability measurements. Each of the four experiments will be discussed separately.

5.9.1 Smith's First Experiment

Smith's (1965) first experiment "was undertaken primarily to obtain underwater threshold data on subjects whose bone conduction audiograms as well as air conduction audiograms are known." Such measurements might help clarify the issue of whether or not underwater hearing is primarily via the bone conduction route. The eight male swimmers employed (research staff) had ages ranging from 27 to 50 years and some exhibited depressed hearing particularly in the 4000 to 8000 Hz region.

The tests were conducted in a small pool having a diameter of 12 ft and a depth of only 28 in. The experimental setup is illustrated in Figure 5-24. (The experimental setup for Smith's second experiment, which will be discussed next, is illustrated in Figure 5-25.) A sound projector was positioned on one side of the pool and the subject near the center. The separation between the swimmer's head and the projector was about 5 ft. An effort was made to remove air in the ear canals by having each subject turn his head from side to side prior to the measurements. He then "lay on his stomach with his head tilted back and rested his chin on a fixed block in the center of the pool so that he faced the sound source."

It was indicated that sound pressure level was measured with an AN/PQM-1A Noise Measuring Set borrowed from the Navy's Underwater Sound Laboratory but there was no description of where in the tank the measurements were made (at or near the swimmer's head position?). The positioning of a reference hydrophone and the probing of the sound field around the subject's head would be critical to such an experiment because of the use of a pool of such small dimensions. Large variations of sound

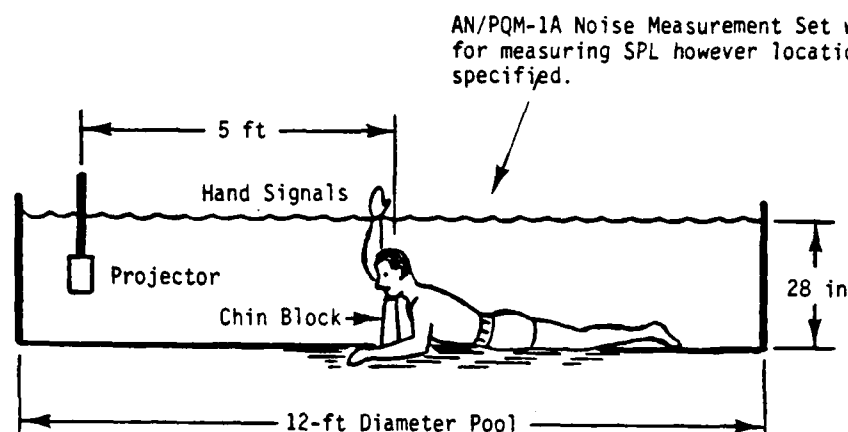


Figure 5-24

Smith's first experiment for determining underwater thresholds of audibility. (After descriptive material provided in Smith, 1965.) 8 breath-holding subjects, swim trunks, weight belt.

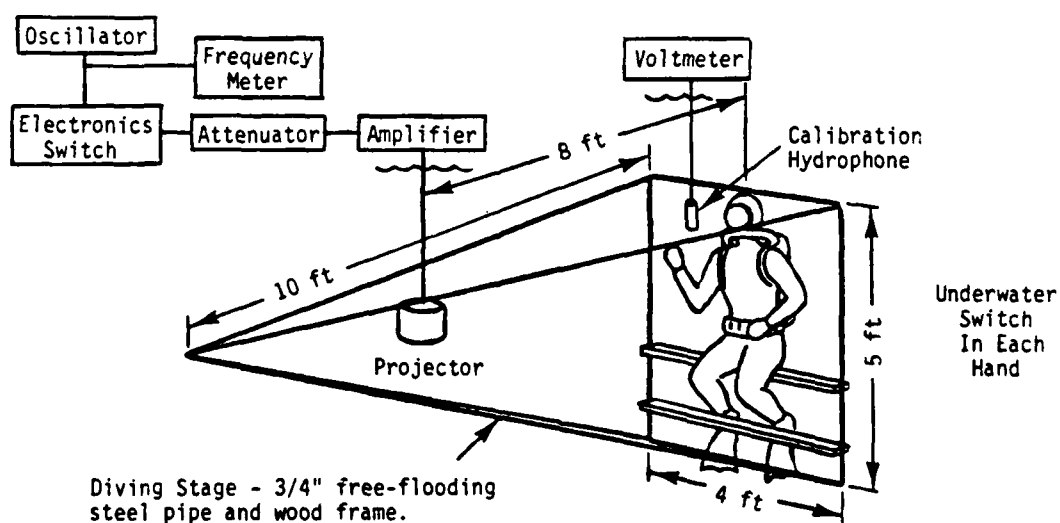


Figure 5-25

Smith's second experiment for determining underwater thresholds of audibility. (After Smith, 1969.) Millstone Quarry Pond, 16 subjects, 15-ft depth in 75-80 ft of water, tests conducted bareheaded and with hoods, open-circuit SCUBA.

pressure would occur over relatively short distances (depending upon frequency) because of multiple reflections from the pool boundaries and resulting standing wave effects. Sound levels could differ significantly with or without the subject in the tank or in position because his body would perturb the standing wave patterns. Further, this setup does not approximate the conditions of a plane or spherical progressive wave impinging upon the subject's head at 0° azimuth (face on) which other experimenters have attempted to approach. Sound would be arriving from all directions and the results obtained could be different from those obtained under near-free-field conditions. Because of the problems associated with this confined environment, one cannot have great confidence that the results, at least in an absolute sense, would be truly representative. Relative measurements (subject to subject) could be reasonably valid if each swimmer was tested in an identical manner relative to positioning of the source, monitor, and head (a head rest or block was used), use of identical frequencies, etc. (In Smith's subsequent experiments, larger bodies of water were selected for performing the underwater tests.)

Air conduction, bone conduction, and water conduction measurements were made at frequencies of 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. The AC and BC data were obtained by conventional audiometry. Although individual audiograms were not presented in the report of the experiment, tabular information containing means and standard deviations for the three types of measurements (AC, BC, and in-water) showed that some of the subjects must have exhibited depressed AC hearing, noticeably at a frequency of 6000 Hz where the mean hearing level over all subjects was +17.4 dB as contrasted with -9.2 dB at 500 Hz. Smith's tabular summary has been reproduced here as Table 5-5 to illustrate this point. We also can see in this table that the mean bone conduction hearing level is not depressed at 6000 Hz as is the AC level, which indicates that one or more of the subjects probably suffered from a conductive hearing loss (versus sensorineural).^{*} This was fortunate (or planned) in Smith's experiment because he was able to use these subjects to provide data to support the hypothesis that the mechanism for underwater hearing is primarily bone conduction.

^{*}It is rare to see an isolated conductive loss at 6000 Hz. This, therefore, raises questions concerning these data.

Table 5-5. Smith's first experiment - means and standard deviations for three types of thresholds.
(From Smith, 1965.)

		<u>Frequency, cycles per second</u>						
		500	1000	2000	3000	4000	6000	8000
Air conduction	M ₁	(-9.2)	(-7.50)	(-3.70)	(2.0)	(6.30)	(17.4)	(3.4)
	M ₂	15.8	9.5	13.3	18.0	21.3	38.4	31.4
	S	5.5	4.8	6.2	5.0	13.2	16.8	15.8
(MAP) better ear								
Bone conduction	M	-11.1	-6.6	-3.3	4.5	0.8	-1.8	-4.0
	S	5.9	5.8	9.8	10.2	8.4	7.7	7.2
better ear								
Water conduction	M	60.5	68.8	81.6	85.6	84.9	87.4	82.1
	S	9.6	11.7	8.9	6.8	17.5	7.7	10.6
(MAF)								

Means for AC and WC are in db re .0002 dynes/cm². Means for BC are in db re audiometric zero. Mean AC values referred to audiometric zero (M₁) are given in parentheses above the MAP values (M₂). AC and BC values given are for the better (more sensitive) ear which is the same ear for both AC and BC in most cases.

In Figure 5-26, Smith has plotted the AC hearing levels (ordinate) versus the difference between threshold sound pressure levels in water and in air. If underwater hearing is primarily by air conduction, then when AC hearing is depressed in-water hearing would also be depressed and the difference would be the same as if there was no hearing loss. However, if hearing is primarily by bone conduction and if AC is depressed but BC is not depressed as at 6000 Hz in Figure 5-27, one would expect to see the linear correlation exhibited at 6000 Hz in Figure 5-26 (there is also an indication of this effect at 8000 Hz where the AC-BC difference is not as pronounced). Smith concluded "on the basis of those results that hearing in water is primarily mediated by bone conduction" but he also recommended "that further studies be undertaken with a larger sample to validate the above findings."

5.9.2 Smith's Second Experiment

The purpose of this experiment was to measure underwater thresholds of audibility for a sample of subjects having varying degrees of hearing sensitivity. 16 male divers from local U.S. Naval activities were tested. According to Smith, "eleven men had normal hearing (no hearing level greater than +10 dB), three had predominantly AC losses at a single frequency (6 kHz) and two had mixed AC and BC losses at some frequencies." (Note: it is possible that some of these subjects were the same as those used in the first experiment, particularly those with the AC losses at 6 kHz.)*

The experimental setup has been illustrated in Figure 5-25. A diving stage made of free-flooding steel pipe and wood was fabricated in the form shown in the figure. Horizontal wooden cross members were provided across the rectangular end of the framework to provide a seat for the diver and a foot support to allow the subject to remain still while having two hands free for signaling. The sound projector was mounted 8 ft from the center of the diver's head and a reference hydrophone was positioned adjacent to his head.

*Again, it is almost unheard of to have subjects with only conductive losses at a single frequency such as 6 kHz.

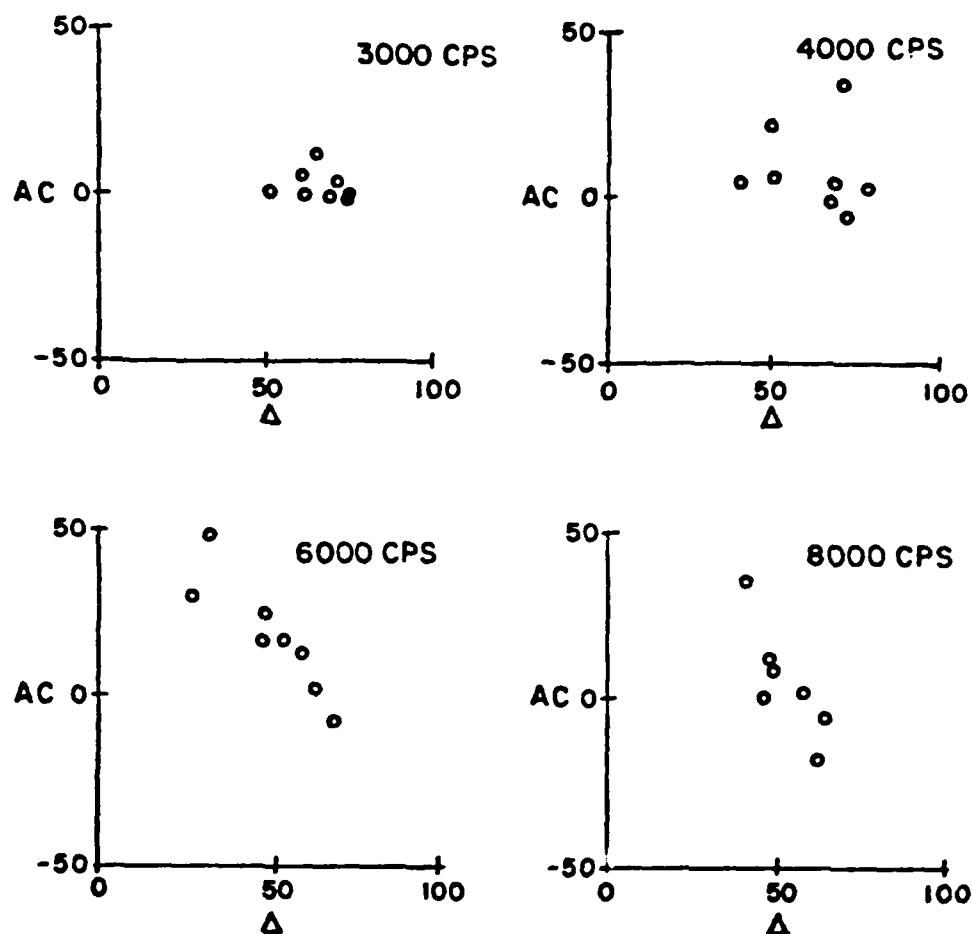


Figure 5-26

The relationship between air conduction hearing levels and the difference between thresholds in water and thresholds in air. The abscissa is the decibel difference between the sound pressure levels at threshold in water and in air. The ordinate is the hearing level in air in decibels re audiometric zero. The plot for 3000 cps is very similar to those for all lower frequencies which are not shown. (From Smith, 1965.)

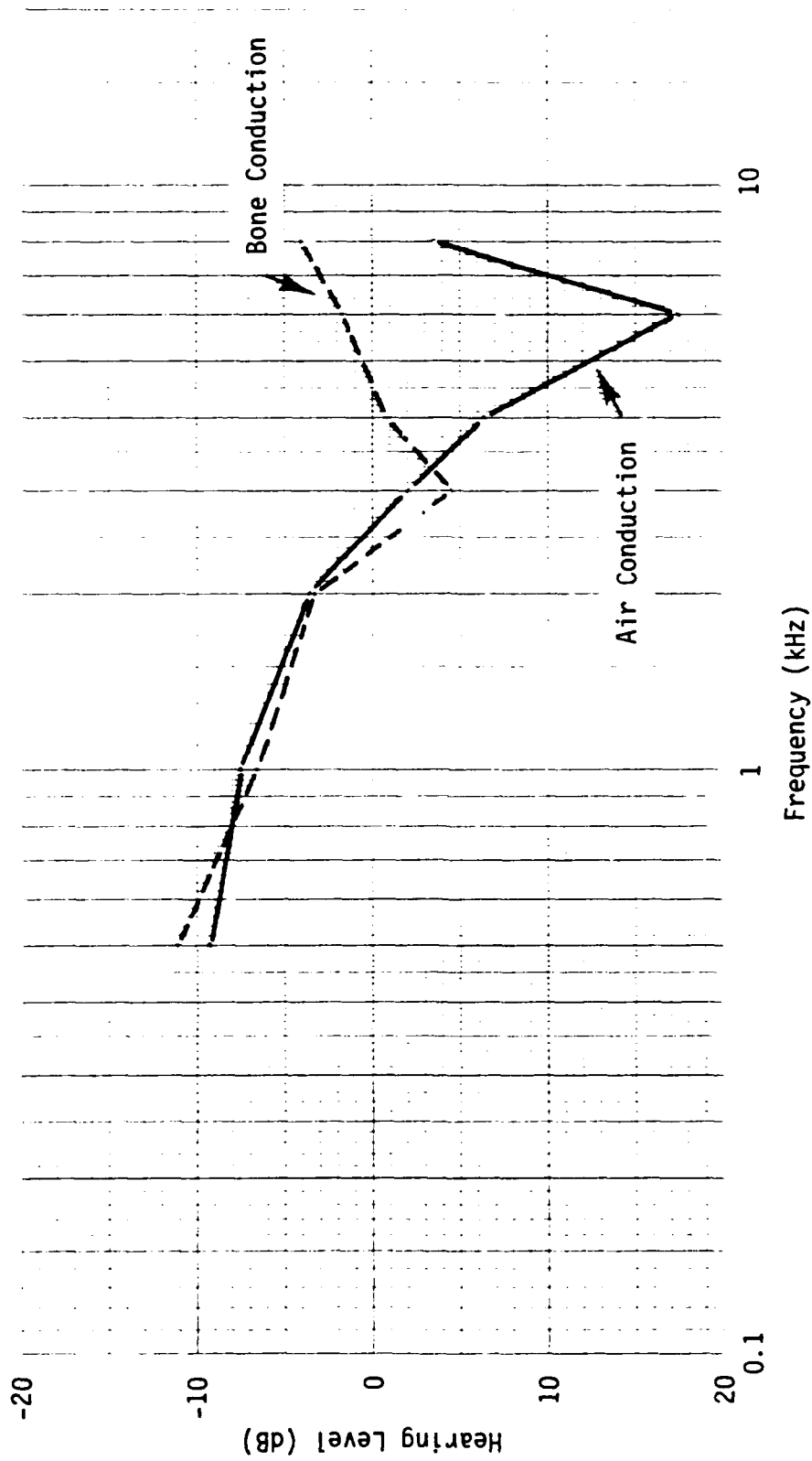


Figure 5-27

Mean air conduction and bone conduction hearing levels for the eight subjects used in Smith's (1965) first experiment.

The tests were conducted in "Millstone Quarry Pond (a fresh water test facility operated by the Navy Underwater Sound Laboratory)." The framework was suspended from a catwalk at a depth of 15 ft in 75-80 ft of water. Experimentally this might appear to be a good arrangement since there would be no barge to provide reflecting surfaces and the quarry bottom was far enough away (and possibly absorptive) to minimize the levels of sound reflected off of that boundary. However, reflections from the near surface of the pond would be present and would produce some lower level (with respect to the direct path signal) interference. Information on the nearness, shape, and reflectivity of the side walls of the Millstone Quarry Pond was not provided (quarries are notorious for having near-vertical hard walls). The diving stage was positioned near the center of the pond. However, if there were any significant sound focussing effects and multiple reflections from the side walls, then there may have been many "echoes" arriving at the location of the diver producing some signal variations with small changes in position. Smith's use of a reference hydrophone would of course provide a measure of the *actual* sound field, including the direct as well as all reflected signals, but only at the location where the hydrophone was placed.

Tones were used for the in-water threshold measurements at frequencies of 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Audiometric AC and BC data were also provided for these same frequencies. The divers were tested both with and without 3/8 in. neoprene and nylon hoods (the hoods were completely removed for testing purposes rather than merely being pushed back off of the head). The subjects wore open-circuit SCUBA and held their breath when the underwater measurements were being made to minimize exhaust bubble noise. It is not clear from the report if the divers wore swim suits or diving suits.

Smith stated that, "on the basis of prior studies, the ambient noise level in the pond was estimated by NUSL personnel to be about 34 dB at one kHz sloping to a lesser level at 8 kHz." Assuming that the 34 dB figure represents a spectrum level, it would correspond to an average deep-water ambient noise level equivalent to Sea State 2 or 3 conditions (Urlick, 1967, page 168)--moderately noisy for a "quiet" pond. The critical bandwidth (BW_C , Hz) for two-ear listening (in the presence of white, random noise) at 1000 Hz is about 40 Hz. The masking effect is obtained by calculating $10 \log_{10} BW_C$, or 16 dB, and adding the result to the ambient noise spectrum level. Thus, 34 dB plus 16 dB equals 50 dB. If the tone is to be heard, its level must exceed 50 dB SPL. Smith's mean underwater threshold at 1 kHz for "eight normal-hearing divers in the bare-headed condition" was about 54 dB; not significantly greater than the critical band noise level

and, therefore, this could be considered a marginal situation. The critical band noise level at 8 kHz is about 23 dB, 6 dB higher than at 1 kHz, but as indicated by NUSL personnel the ambient noise (spectrum) level was less at 8 kHz. Furthermore, Smith's underwater threshold data showed the required sound pressure level of the tone at 8 kHz to be 78 dB (vice 54 dB at 1 kHz). Masking probably would not be a problem at the higher frequencies.

Because of reflections from the pond surface (or possibly other boundaries), Smith may have had some difficulty with SPL variations associated with standing wave effects. He stated that "measurements indicated no significant differences in SPL across the rectangular portion of the stage at the level of the diver's head." However, he did not say that such measurements were made at all frequencies. The uniformity of SPL in the vicinity of the diver's head would depend upon frequency since the in-water wave lengths would vary from about 5 ft at 1 kHz to 0.6 ft at 8 kHz. At the higher frequencies, small changes in the position of the subject's head (vertically as well as horizontally) could significantly vary the results of the test. Smith also stated that "because of the proximity to the surface and the rather large subject-to-sound-source distance, it was necessary to use a frequency discriminator to insure exact replication of test frequencies from trial to trial since very slight errors in setting the frequency resulted in as much as 7-10 dB differences in SPL at the diver's head." This statement is indicative of the standing wave problem.

The threshold results of Smith's second experiment for eight bareheaded divers with normal hearing are shown in Figure 5-28. The effect of the attenuation provided by the diver's hood is also shown in this figure. The subjects used in the latter test included two normal hearing men "not represented elsewhere" and one man with depressed BC hearing (on the basis of this description it is unclear as to the total number of subjects used). Smith states that "the data in Figure 13 (our Figure 5-28, lower half) are based upon relative signal input levels." This statement suggests that the reference hydrophone was not used to measure the SPL difference (loss) for the hood-versus-no hood conditions.

Of Smith's sixteen subjects, two had both AC and BC hearing losses and three had AC losses *without* significantly depressed BC hearing. This latter condition is somewhat unusual in a statistical sense. The most common form of hearing loss is sensorineural in which both AC and BC hearing losses are evident--they would track together in an audiogram because the damage has occurred in the cochlea or beyond (e.g., hair cell loss, etc.). As in Smith's first experiment, these individuals may have been

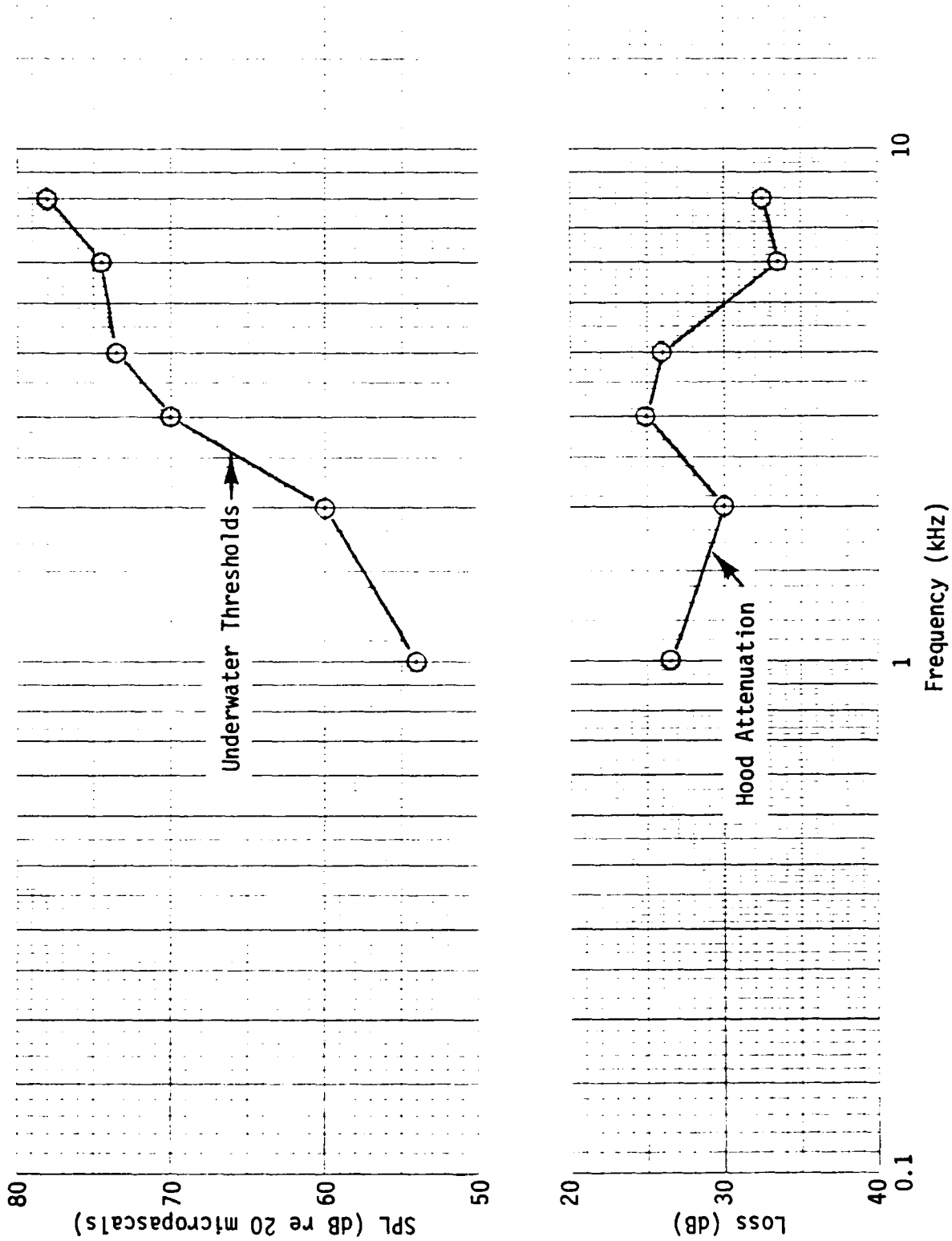


Figure 5-28

Smith's second experiment - Mean underwater hearing thresholds for eight bareheaded divers with normal hearing, and attenuation provided by 3/8" foam Neoprene wet suit hood. (After Smith, 1969.)

purposely selected in order to provide further evidence on the bone conduction theory of underwater hearing. More than one investigator has suggested using subjects underwater having conductive hearing losses but not sensorineural losses (such as otosclerotic subjects*) to obtain data related to the mechanism for underwater hearing. Indeed, the evidence from Smith's second experiment "indicates that depressed air conduction hearing levels are not reflected in depressed underwater sensitivity, unless the depressed air conduction hearing level is accompanied by depressed bone conduction sensitivity."

Smith has placed great emphasis on the need to obtain both AC and BC audiometric data on subjects used in these underwater experiments. This is certainly true when dealing with the question of the mechanism for underwater hearing. However, the lack of BC audiometric data in other experiments is probably not a serious deficiency for underwater threshold measurements if a number of young divers are included in the sample. AC audiometric measurements would identify the few with hearing problems. It is essentially impossible for individuals to have deficient BC hearing and normal AC hearing.

One final point of interest will be mentioned. In those papers in which the various investigators have not presented the actual in-air audiometric data (i.e., hearing levels) but rather have converted their measurements to thresholds of audibility in terms of sound pressure levels, it has not been clear how this "conversion" was accomplished. Table 5-5 which was duplicated from Smith's (1965) report provides a clue as to how *he* did it since he has provided both hearing levels and sound pressure levels (which he calls "MAP values"). The following Table 5-6 lists the differences between his audiometric data and SPL data, and compares the differences with the audiometric standards (MAPC reference values) of ASA Z24.5-1951 which were in effect in the U.S. at the time of Smith's experiment. We see that Smith's conversion values generally agree *exactly* with the ASA-1951 MAPC reference values except at 1000 Hz where the difference is only 0.5 dB and at 8000 Hz where there is a large difference of 7 dB. The ASA-1951 reference MAPC values applied to the Western Electric 705-A earphone and NBS 9-A coupler. Perhaps the larger difference at 8000 Hz (if not a "typo") was due to the use of a different earphone which might depart from the 705-A values at the higher frequencies. Nevertheless, it does appear that the ASA-1951 standards formed the basis for

*Otosclerosis: An abnormal growth of bone at the base of the stapes in the oval window which results in progressive deafness (possibly hereditary.)

converting, by simple addition, the hearing level data to SPL data and that the results so obtained would not accurately reflect equivalent MAF (free-field) values.

5.9.3 Smith's Third Experiment

Smith's third experiment, described as the "Subsidiary Experiment" in his 1969 report, was conducted to determine the effect of depth on the acoustic protection provided by the diver's hood. Two divers who had participated in the previous tests were used. The measurements were performed in the Escape Training Tank of the Navy Submarine School. This tank probably was a highly reverberant environment with many standing waves patterns and therefore SPL measurements with a reference hydrophone around the diver's head position would be very important. The apparatus for the underwater threshold measurements was the same as used at Millstone Quarry Pond except that a different projector was used and a continuously variable attenuator was added in series with an existing decade attenuator.

Underwater thresholds of audibility measurements were made at frequencies of 250, 1000, and 4000 Hz and at depths of 33, 66, and 99 ft with and without 3/8 in. nylon-lined Neoprene hoods. The 66-ft data were not useful since, "inadvertently, one diver did not remove his hood at 66 feet" and the "other diver kept his on during both runs" at that depth. Therefore, only data at 33 and 99 ft were obtained under valid hood-no hood conditions.

The submarine Escape Training Tank proved to be too noisy for valid bareheaded threshold measurements even though all non-essential machinery was turned off and the experiment was conducted during the evening hours. Therefore the data obtained *with* hoods had to be compared with previous data taken at Millstone Quarry Pond at 15 ft depth. The results with hoods, at 1 and 4 kHz (and, we assume, at both 33 and 99 ft depths) were reported to be the same as at the pond (250 Hz data were not obtained at the pond) and, therefore, it appears that the attenuating properties of the hood are effective up to depths of about 100 ft at these frequencies. (Note: Smith did not present the data taken at the Escape Training Tank in the 1969 report.)

Smith cautions that:

"The results for depths to 99 feet indicate that the attenuating properties of diver's hoods may not be due to the pressure release action of the entrapped air cells. Since the

Table 5-6. Comparison of the difference between Smith's (1965) values for converting hearing level to sound pressure level and the MAPC reference values of ASA Z24.5-1951.

<u>Frequency</u>	<u>Audiometric Hearing Level</u>	<u>SPL</u>	<u>Δ (SPL-HL)</u>	<u>MAPC ASA 1951</u>	<u>Δ-MPAC 1951</u>
500	-9.2	15.8	25.0	25.0	0.0
1000	-7.5	9.5	17.0	16.5	0.5
2000	-3.7	13.3	17.0	17.0	0.0
3000	2.0	18.0	16.0	----	---
4000	6.3	21.3	15.0	15.0	0.0
6000	17.4	38.4	21.0	----	---
8000	3.4	31.4	28.0	21.0	7.0

HL values in dB re audiometric zero.

SPL values in dB re 20 μ Pa.

volume of these cells is diminished considerably at 99 feet, the hood's ability to act as a pressure release device is diminished."

Further:

"Informal observations in a small swimming pool and at Millstone (Pond) tended to corroborate Montague and Strickland's observation that varying thickness of hoods (from 1/8" to 3/8") had similar effects on thresholds. However, loose fitting hoods did not seem to provide as much attenuation as well fitting or tightly fitting hoods. Furthermore, as Montague and Strickland indicated, the amount of bone exposed to the water also seems to be important. Harris²⁹ observed that lifting the hood away from one cheek bone had the effect of increasing the loudness of a 3.5 kHz pure tone by about 15 dB. These observations also tend to favor the view that the damping effect of the hood on the skull rather than a pressure release effect produces the observed attenuation."*

However, a snugly fitting hood would appear to offer a fair amount of protection against high noise levels at frequencies of 1 kHz and above.

5.9.4 Smith's Fourth Experiment

Because other investigators had reported variability in underwater threshold measurements, Smith's fourth and final experiment was conducted to establish the repeatability of such measurements. (This was the third experiment in his 1969 report.)

*The cause of the attenuation provided by hoods (i.e., air cells versus skull damping) has not yet been unambiguously determined. Some additional experimentation which may help answer this question is recommended in Section 6 of this report.

Five bare-headed subjects with "normal BC hearing levels" were used. Three of the five had been involved in previous work. Measurements were made at frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, however, distortion of the output signal occurred below 250 Hz. (An effort was made to obtain data down to 32 Hz, however, because of transducer limitations the distortion was extreme at this low frequency.) Each diver was tested three or four separate times with at least 24 hours between tests. The test depth was 20 ft instead of the 15-ft depth used at Millstone Quarry Pond in Smith's second experiment.

Smith does not explicitly state where the repeatability tests were conducted. He does indicate that the equipment used was the same as in the previous experiment with the exception of the power amplifier for driving the projector, and that the procedures were basically the same as used in the second experiment. He also indicated that the "electronic equipment was mounted in a building some distance from the diving site, necessitating running about 150 feet of cable."

The results of the repeatability measurements are reproduced here in Table 5-7. Standard deviations were not provided. Rather, the values under the frequency columns are the differences between the highest and lowest thresholds (spread) obtained over the number of trials indicated in the second column. The final column gives the mean spread values over all frequencies. Smith noted that the greatest variability occurred for the two divers with the most diving experience but also that "the variation from trial to trial for the younger divers is almost within the limits of good clinical audiometry."

The average underwater threshold values for the five divers used in the fourth experiment are plotted in Figure 5-29. The dashed portion of the data represents the region of signal distortion previously mentioned. The data from 1000 to 8000 Hz agree fairly closely with the data for the eight "normal" hearing subjects in Smith's second experiment (see Figure 5-28). However, the data are somewhat unusual in the character of the sharp dip at 1000 Hz and the peak at 500 Hz--the difference in threshold values over this 500 Hz range is almost 20 dB. There is also a 20 dB rise from 1000 Hz to 4000 Hz. As a consequence of these characteristics, Smith's curve "crosses over" the curves of most other investigators both below and above 1000 Hz, although above 1000 Hz the departure is not too significant because the data of other investigators also exhibit a positive slope. The pronounced negative slope from 500 to 1000 Hz, however, goes counter to the measurements of others in this frequency range where generally the

Table 5-7. Variability of underwater threshold measurements. (From Smith, 1969.)

Subject No.	Number of Trials	Years Diving	Frequency (Hz)							Subjects Mean Range
			125	250	500	1000	2000	4000	8000	
1	3	2	11	8	23	11	6	6	3	9.71
2	3	5-6	10	11	5	7	11	1	7	7.42
3	4	2	5	5	1	7	5	7	24	7.71
4	4	18-20	17	11	4	19	16	12	29	15.42
5	4	18-20	8	9	14	23	17	20	3	13.42
Mean Ranges			10.2	8.8	9.4	13.4	11.0	9.2	13.2	10.73

Notes: (1) Entries under frequency headings are the differences between the highest and lowest threshold measurements observed for each subject over the number of trials indicated in the second column.

(2) The third column gives the approximate length of diving experience for each subject.

slopes of the curves are nearly flat or slightly positive. One might suspect the data point at 500 Hz as being non-representative of the true population, but there is no clear explanation for such a discrepancy.

Smith attempted to normalize his data by adjusting the threshold values obtained in his first (small pool), second (Millstone Quarry Pond), and fourth experiment using the measured bone conduction hearing levels for the various subjects. The general character of the curves obtained from the three experiments remained about the same although the relative positions changed somewhat. This adjustment process did not eliminate the discrepancies between the first and later experiments nor did it eliminate the apparent anomaly at 500 Hz.

Again we must remind ourselves that Smith's fourth experiment was conducted at the time (1967) that the old audiometric standards were still in effect in the U.S. (ASA-1951). All of Smith's AC audiometric data may need to be adjusted to relate his values to the reference threshold levels of ANSI S3.6-1969 if we are to make comparisons between old and new data.

The problem of reference thresholds of audibility for bone-conducted sound is not quite as clear. In ANSI S3.6-1969 it is stated that:

"The reference threshold for audibility for bone-conducted sound is the median value of threshold determinations on a large number of otologically normal ears of individuals between 18 and 30 years of age. These reference threshold values, expressed in absolute units, are now in process of determination, as is also the choice of suitable means for storing the data and for transference to other vibrators."

One might reasonably assume that the manufacturers of audiometers with both earphone and bone vibrator capabilities would provide signal levels to each device that tracked together--i.e., levels that would be representative of young otologically normal ears at 0 dB HL. The appropriate reference levels for "young normal ears" would depend upon the standard in force at the particular time of the experiments--ASA-1951 or ANSI-1969. If this assumption is true, then Smith's BC data would have to be adjusted similarly to AC data in order to make comparisons with new data. (Reference equivalent threshold force levels for audiometric bone vibrators have more recently been provided in ANSI S3.26-1981 (ASA 41-1981) where it is stated that the specified "threshold force levels

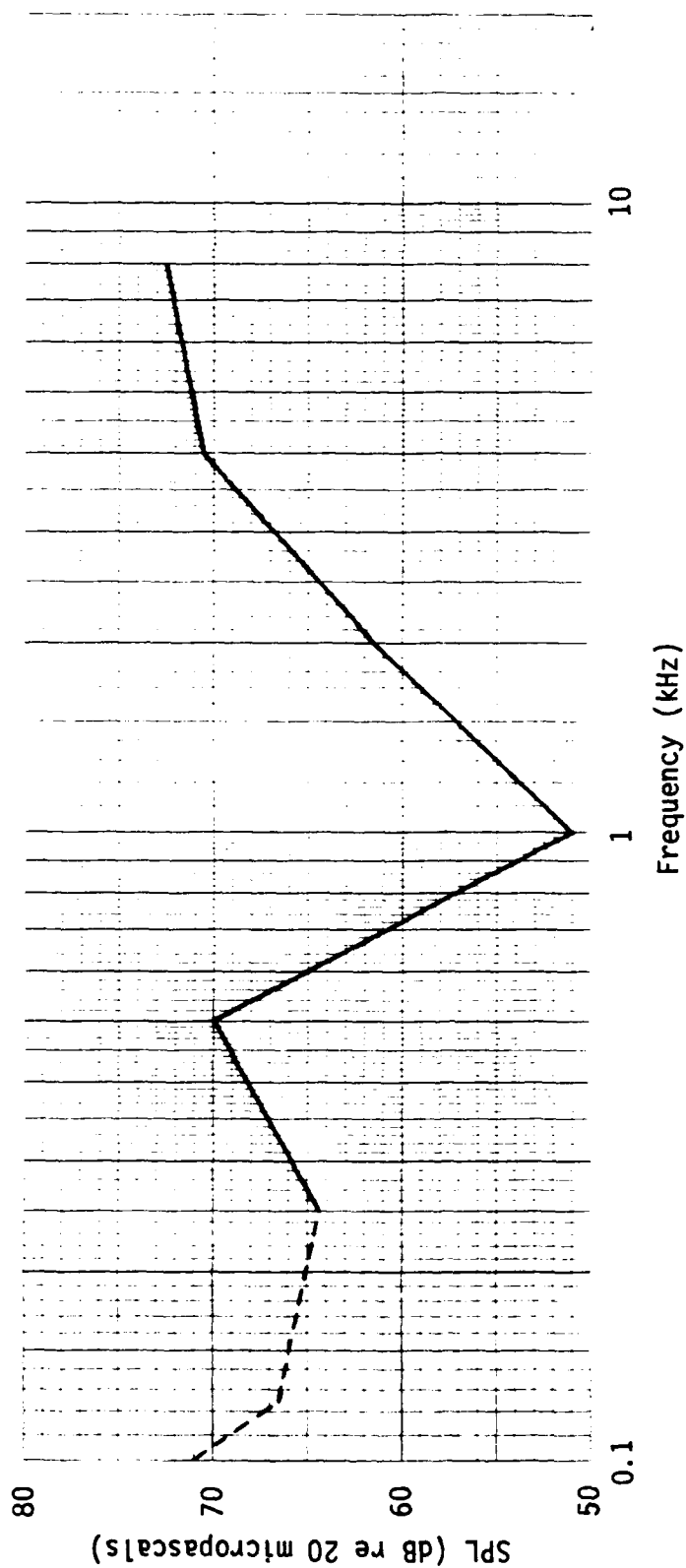


Figure 5-29

Smith's fourth experiment (repeatability) - Mean underwater hearing thresholds for five men with no significant bone conduction hearing deficiency. (After Smith, 1969.)

correspond to thresholds for normal hearing persons by air conduction as specified in ANSI S3.6-1969.")

5.10 Experiments on the Threshold of Audibility Under Water; Analysis, Summary, and Conclusions

5.10.1 Selection of the Better Experiments

The results obtained from the experiments conducted between 1943 and circa 1970 on underwater thresholds of audibility have been quite varied, the differences being too large to establish with any confidence the actual behavior of the "normal young ear" in the underwater environment. The purpose of the review just conducted was to evaluate the quality of the numerous experiments with the intent of sorting out the more reliable data from that which might be questionable and establishing a better estimate of actual underwater hearing sensitivity.

The experiments have been performed under a variety of conditions and degrees of thoroughness, the only common element being that all of the investigators used tones for the underwater signals. Some of the key deficiencies and problems noted have included high or unknown ambient noise levels, a lack of monitoring of the actual sound field around the diver's head position, and a lack of objective information on the quality of the subject's hearing--i.e., in-air audiometric data. If a subject has poor hearing in air, he or she is likely in a statistical sense to have poor hearing in water and the underwater thresholds will be elevated and therefore not representative (statistically, sensorineural losses are the most common and will result in poor hearing both in air and under water). If the sound field is not monitored by use of a reference hydrophone, then large uncertainties in underwater thresholds may exist because of sound reflections and resulting standing wave patterns. If the underwater environment is noisy, then thresholds will also be elevated and nonrepresentative.

The results of some of the experiments can be set aside on the basis of key deficiencies. These include the following:

- Sivian (1947) - A preliminary and limited experiment. No measurements of underwater sound levels were made, and high ambient noise levels for in-air listening existed. Both in-air and underwater data were therefore questionable.

- Ide (1944) - The report of the experiment lacked detail. Questions exist regarding underwater sound level monitoring, ambient noise levels, and in-air hearing assessment of the subjects.
- Reysenbach de Haan (1956) - Underwater sound levels were not measured at the subjects position but were extrapolated (probably incorrectly) from short-range measurements. In-air audiometric data were not provided. Information on ambient noise was not provided.
- Wainwright (1958) - There was no evidence of use of a reference hydrophone to measure the underwater sound levels. The average in-air MAF data for the two subjects used appeared anomalous. Original audiometric data were not presented. The subjects may have had depressed hearing.
- Montague and Strickland (1961) - A reference hydrophone was not used to measure SPL at the diver's head position. There was no mention of ambient noise conditions. Although audiometric data were obtained, the actual hearing levels were not presented. Rather, "MAP thresholds" (instead of MAF) were presented but the conversion process was not described.

The remaining experiments, namely those of Hamilton, Hollien *et al.*, and Smith, are considered to be reasonably thorough and therefore were not totally deficient in regards to the key areas mentioned above. Although there were some problems and uncertainties noted, it is worthwhile to look at the results obtained from this group of tests alone and thereby eliminate the possible contamination of questionable data from those experiments with known major deficiencies.

5.10.2 Collation of the Underwater Threshold Data of Hamilton, Hollien et al., and Smith

Hamilton's mean underwater threshold levels for his four subjects (no hoods) are listed in the second column of Table 5-8. Corrections for the subjects' measured hearing levels (third column) and for the change in audiometric standards introduced by ISO-1964/ANSI-1969 (fourth column) have been made to Hamilton's underwater thresholds to produce the results shown in the last column of this table. These results are plotted in Figure 5-30.

Three of the four experiments conducted by Hollien *et al.* included measurements of both underwater thresholds and audiometric hearing levels. As suggested previously in Figure 5-23, Hollien may have converted his in-air HL data (which were not presented in original form in his papers) to equivalent free-field SPL data using the reference MAPC values of ASA Z24.5-1951 (instead of the appropriate MAF curve). Let us assume that this is what was done--we can then reconstruct the original HL data.

Table 5-9 presents Hollien's (1967) in-air thresholds for eight bareheaded subjects at 35-ft ear depth. The in-air thresholds are first adjusted in accordance with Hollien's own recommendation to subtract 13 dB from the values at 1000 Hz and below. (The uncorrected data were taken using underwater hydrophone signals routed to earphones for the in-air tests. The underwater and in-air environments were subsequently judged to be too noisy for valid audiometric measurements in the lower frequency range. The 13 dB correction was derived from later additional laboratory measurements.) The corrected in-air thresholds are then converted to reconstructed mean hearing levels--the last column in the table--by subtracting the ASA-1951 MAPC reference values.

Given the mean hearing levels for Hollien's eight divers, we can now correct the underwater thresholds for these hearing levels and for the change in audiometric standards brought about by ANSI-1969 as was done in the case of Hamilton's data. The results are shown in Table 5-10 and are also plotted in Figure 5-30.

Hollien and Brandt (1969) studied the effect of air bubbles in the ear canal on underwater thresholds. In this experiment, a Rudmose automatic audiometer was used to obtain in-air thresholds rather than the underwater hydrophone-to-earphone system used in the previous experiment. Table 5-11 lists the mean in-air thresholds obtained and the reconstructed mean hearing levels using the ASA-1951 MAPC values. Table 5-12 lists the mean underwater thresholds, the adjustments for hearing levels, and the corrections for the ANSI-1969 standards. Hollien and Brandt found no significant difference

Table 5-8. Hamilton's underwater thresholds corrected for subjects' hearing levels adjusted to ANSI-1969 standards.

(1) Freq (Hz)	(2) Mean Underwater Threshold (dB)	(3) Mean Hearing Level (dB)	(4) Correction for ANSI-1969 (dB)	(5) Corrected Threshold (2)-(3)-(4) (dB)
250	60	-1	15.0	46.0
500	52	0	14.0	38.0
1000	53	1	10.0	42.0
2000	53	-9	8.5	53.5
4000	55	-6	6.0	55.0

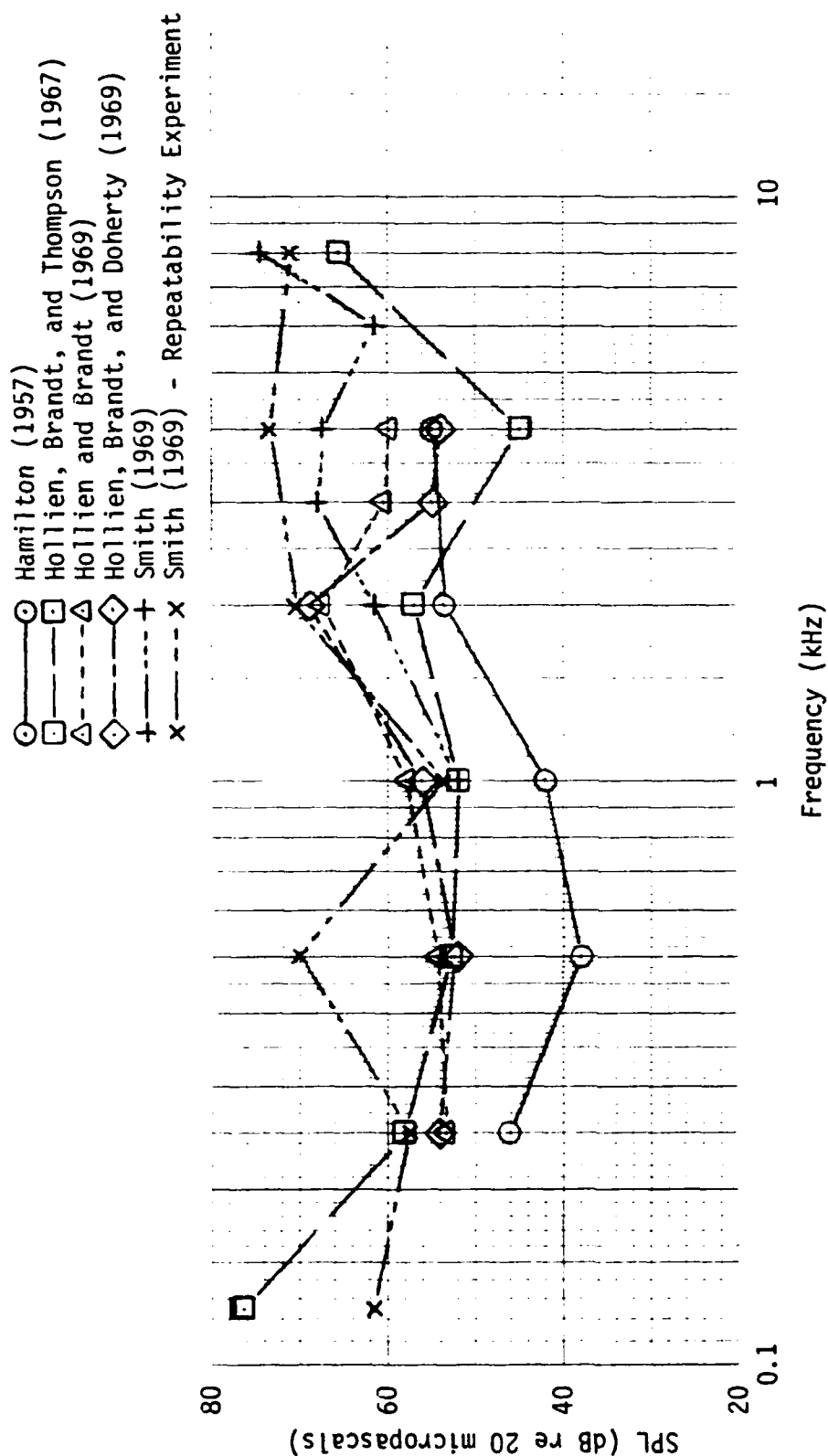


Figure 5-30

Mean underwater thresholds of audibility from the six best experiments. The data have been normalized on the basis of the subjects' hearing levels and have been corrected to the audiometric standards of ANSI S3.6-1969.

Table 5-9. Reconstructed mean hearing levels for eight subjects used in the underwater threshold experiment of Hollien, Brandt, and Thompson (1967).

Freq (Hz)	In-Air Threshold (dB)	Corrected In-Air Threshold ¹ (dB)	ASA-1951 MAPC Values (dB)	Reconstructed Mean Hearing Levels (dB)
125	51.8	38.8	54.5	-15.7
250	43.8	30.8	39.5	-8.7
500	29.5	16.5	25.0	-8.5
1000	27.3	14.3	16.5	-2.2
2000	17.4	17.4	17.0	0.4
4000	31.1	31.1	15.0	16.1
8000	17.7	17.7	21.0	-3.3

¹13 dB has been subtracted from the in-air thresholds at 1000 Hz and below in accordance with Hollien's (1967) recommendation in footnote 1, page 969 of the reference.

Table 5-10. Hollien's (1967) underwater thresholds corrected for subjects' hearing levels adjusted to ANSI-1969 standards.

(1) Freq (Hz)	(2) Mean Underwater Threshold (dB)	(3) Mean Hearing Level (dB)	(4) Correction for ANSI-1969 (dB)	(5) Corrected Threshold (2)-(3)-(4) (dB)
125	69.6	-15.7	9.0	76.3
250	64.5	-8.7	15.0	58.2
500	58.4	-8.5	14.0	52.9
1000	59.8	-2.2	10.0	52.0
2000	65.9	0.4	8.5	57.0
4000	67.2	16.1	6.0	45.1
8000	73.9	-3.3	11.5	65.7

between the thresholds obtained with and without air bubbles in the ear canal and therefore their average underwater threshold values for the two conditions have been used. The last column in Table 5-12 contains the corrected thresholds which have also been plotted in Figure 5-30.

In similar fashion, Tables 5-13 and 5-14 show the reconstructed mean in-air hearing levels and the corrected underwater thresholds using the data of Hollien, Brandt, and Doherty (1969). In this experiment, the investigators were studying the effect of depth on underwater hearing thresholds. Six divers and three depths were used--35, 70, and 105 ft. No significant difference was found as a function of depth. Therefore, the underwater threshold values listed in Table 5-14 represent averages over all depths. Again, the corrected underwater thresholds are plotted in Figure 5-30.

Smith (1969) conducted underwater threshold measurements on eight subjects judged to have normal hearing. In-air audiometric hearing levels for both air conduction (AC) and bone conduction (BC) were presented in his report. He also conducted a series of underwater threshold *repeatability* measurements on five normal hearing divers, however, only BC hearing level data were presented in his report for this portion of the experiment. To be consistent with our previous calculations, we would have liked to have adjusted both sets of Smith's data using AC hearing levels, but we are forced to use BC levels for the repeatability experiment data. For "normal hearing" individuals, it is expected that on the average AC and BC hearing levels will track together reasonably well and, therefore, the use of BC levels for the last data set is not considered to be a serious deficiency in this analysis. Tables 5-15 and 5-16 present the corrected underwater thresholds for Smith's initial experiment using eight divers and the repeatability tests using five divers. The corrected threshold data are also plotted in Figure 5-30.

In summary, Table 5-17 lists the corrected underwater thresholds of audibility for the six experiments conducted by Hamilton, Hollien *et al.*, and Smith. Also provided are the means and standard deviations (σ) at each frequency for all data available at that frequency. Standard deviations were not calculated when n was less than 3. The average standard deviation over all frequencies was 7.1 dB. Killion's (1978) in-air binaural MAF data for 0° incidence, based upon ISO R226-1961 but with a low frequency (below 500 Hz) correction, are given near the bottom of Table 5-17. The SPL differences between these representative in-air MAF values and the mean underwater threshold values are given in the bottom line of this table. The differences range from about 39 to 64 dB with a mean difference of 52.4 dB over the range of 125 to 8000 Hz. The mean

Table 5-11. Reconstructed mean in-air hearing levels for seven subjects used in the experiment of Hollien and Brandt (1969) on the effect of air bubbles in the ear canal.

<u>Freq (Hz)</u>	<u>In-Air Threshold (dB)</u>	<u>ASA-1951 MAPC Values (dB)</u>	<u>Reconstructed Mean Hearing Levels (dB)</u>
250	39	39.5	-0.5
500	25	25.0	0.0
1000	19	16.5	2.5
2000	9	17.0	-8.0
3000	18	(16.0)	2.0
4000	23	15.0	8.0

() Interpolated value.

Table 5-12. Hollien and Brandt (1969) underwater thresholds corrected for subjects' hearing levels adjusted to ANSI-1969 standards.

(1) Freq (Hz)	(2) Mean Underwater Threshold ¹ (dB)	(3) Mean Hearing Level (dB)	(4) Correction for ANSI-1969 (dB)	(5) Corrected Threshold (2)-(3)-(4) (dB)
125	70.8	----	9.0	----
250	68.0	-0.5	15.0	53.5
500	(68.5)	0.0	14.0	54.5
1000	70.4	2.5	10.0	57.9
2000	68.1	-8.0	8.5	67.6
3000	(71.0)	2.0	8.5	60.5
4000	(74.0)	8.0	6.0	60.0
8000	81.3	----	11.5	----

¹Average of "air bubble" and "no air bubble" mean thresholds. There was no significant difference between the thresholds for the two conditions.

() Interpolated values.

Table 5-13. Reconstructed mean in-air hearing levels for six subjects used in the experiment of Hollien, Brandt, and Doherty (1969) on the effect of depth on underwater thresholds.

<u>Freq (Hz)</u>	<u>In-Air Threshold (dB)</u>	<u>ASA-1951 MAPC Values (dB)</u>	<u>Reconstructed Mean Hearing Levels (dB)</u>
250	37.5	39.5	-2.0
500	26.0	25.0	1.0
1000	17.8	16.5	1.3
2000	11.2	17.0	-5.8
3000	28.0	(16.0)	12.0
4000	31.0	15.0	16.0

() Interpolated value.

Table 5-14. Hollien, Brandt, Doherty (1969) underwater thresholds corrected for subjects' hearing levels adjusted to ANSI-1969 standards.

(1) Freq (Hz)	(2) Mean Underwater Threshold ¹ (dB)	(3) Mean Hearing Level (dB)	(4) Correction for ANSI-1969 (dB)	(5) Corrected Threshold (2)-(3)-(4) (dB)
125	67.2	----	9.0	----
250	67.2	-2.0	15.0	54.2
500	(67.4)	1.0	14.0	52.4
1000	67.5	1.3	10.0	56.2
2000	71.6	-5.8	8.5	68.9
3000	(74.0)	12.0	(7.0)	55.0
4000	(76.0)	16.0	6.0	54.0
8000	80.1	----	11.5	----

¹Average over three depths of 35, 70, and 105 ft. There was no significant difference in threshold values with depth.

() Interpolated values.

Table 5-15. Smith's (1969) underwater thresholds corrected for subjects' hearing levels adjusted to ANSI-1969 standards (eight subjects with normal hearing).

(1) Freq (Hz)	(2) Mean Underwater Threshold (dB)	(3) Mean Hearing Level (dB)	(4) Correction for ANSI-1969 (dB)	(5) Corrected Threshold (2)-(3)-(4) (dB)
1000	54.0	-8	10.0	52.0
2000	60.0	-10	8.5	61.5
3000	70.0	-5	(7.0)	68.0
4000	73.5	0	6.0	67.5
6000	74.5	3	(10.0)	61.5
8000	78.0	-8	11.5	74.5

() Interpolated values.

Table 5-16. Smith's (1969) underwater thresholds from his repeatability experiment corrected for subjects' hearing levels adjusted to ANSI-1969 standards (five subjects with normal hearing).

(1) Freq (Hz)	(2) Mean Underwater Threshold (dB)	(3) Mean Hearing Level ¹ (dB)	(4) Correction for ANSI-1969 (dB)	(5) Corrected Threshold (2)-(3)-(4) (dB)
125	66.5	-4.0	9.0	61.5
250	64.5	-8.0	15.0	57.5
500	70.0	-14.0	14.0	70.0
1000	51.0	-12.5	10.0	53.5
2000	61.5	-17.5	8.5	70.5
4000	70.5	-9.0	6.0	73.5
8000	72.5	-10.0	11.5	71.0

¹These are bone conduction hearing levels. Air conduction levels were not presented in the repeatability experiment portion of Smith's report.

corrected underwater thresholds from the six experiments have been plotted in Figure 5-31 along with Killion's MAF curve. The differences between the underwater and in-air thresholds are represented by the dashed curve.

There are two possible outliers in the underwater threshold data set that are worth mentioning (refer to Figure 5-30): the high data point (70 dB) in Smith's repeatability experiment at 500 Hz which appeared as an inconsistency (a jump) in his original underwater threshold plot, and the low data point (45 dB) at 4000 Hz in Brandt and Hollien's (1967) experiment which was caused primarily by an inconsistent jump in their original in-air SPL plot. (Note also the large standard deviations at these two frequencies in Figure 5-31.) The latter inconsistency might be attributed to the frequently observed sensorineural hearing loss (audiogram notch) occurring in mid-age and older subjects at 4000 to 6000 Hz, however, there was no evidence of a significant discontinuity in the underwater thresholds at these frequencies which would be expected if such were the case. Without these two outliers, the typical (average) spread in the data over all frequencies is about 15 dB which is significantly less than the range observed when uncorrected data from all experiments are included in the overview (average spread 25 dB or greater). By applying a logical selection/rejection process we are now approaching a condition in which there is better consistency in the results obtained by different investigators--i.e., a one-half spread value of about 7-1/2 dB (or an experiment-to-experiment standard deviation of about 6 dB without the two outliers mentioned above). Indeed, in Smith's repeatability experiment, he observed trial-to-trial mean spreads over all frequencies which ranged from 7.4 to 15.4 dB depending upon the subject, with individual spreads at any given frequencies being as large as 29 dB. Smith's results would not include any additional differences from systematic biases that might be introduced by other experimenters in their choice of such factors as the test environment, instrumentation, and calibration methods.

One caution should be mentioned. The data for the six experiments shown in Figure 5-30 are not completely independent since Hollien *et al.* (three experiments) and Smith (two experiments) used much of the same equipment in their different tests and probably some of the same subjects. On the other hand, there are at least three independent sets of data corresponding to the work represented by the three independent investigators. Figure 5-32 shows an average curve for Hollien's three experiments, an average curve for Smith's two experiments, and Hamilton's single curve. An overall average of the three curves is also shown (solid curve). (This overall average curve generally agrees within 1 or 2 dB with the average curve in Figure 5-31.) The values below

Table 5-17. Mean underwater threshold of audibility as a function of frequency based upon the experiments of Hamilton, Hollien et al., and Smith

- and -

comparison of underwater and in-air thresholds.

Experiment	Mean Underwater Thresholds of Audibility, dB SPL								
	Frequency, Hz								
	125	250	500	1000	2000	3000	4000	6000	8000
Hamilton (1957)	----	46.0	38.0	42.0	53.5	----	55.0	----	----
Hollien (1967)	76.3	58.2	52.9	52.0	57.0	----	45.1	----	65.7
Hollien and Brandt (1969)	----	53.5	54.5	57.9	67.6	60.5	60.0	----	----
Hollien, Brandt, and Doherty (1969)	----	54.2	52.4	56.2	68.9	55.0	54.0	----	----
Smith (1969)	----	----	----	52.0	61.5	68.0	67.5	61.5	74.5
Smith (1969) Repeatability	61.5	57.5	70.0	53.5	70.5	----	73.5	----	71.0
Mean	68.9	53.9	53.6	52.3	63.2	61.2	59.2	----	70.4
σ	----	4.9	11.3	5.6	6.9	6.5	10.2	----	4.4
n	2	5	5	6	6	3	6	1	3
Killion (78)	28.0	15.0	6.0	4.2	1.0	-2.9	-3.9	4.6	15.3
In-air MAF									
Difference, UW-Air (dB)	40.9	38.9	47.6	48.1	62.2	64.1	63.1	----	55.1

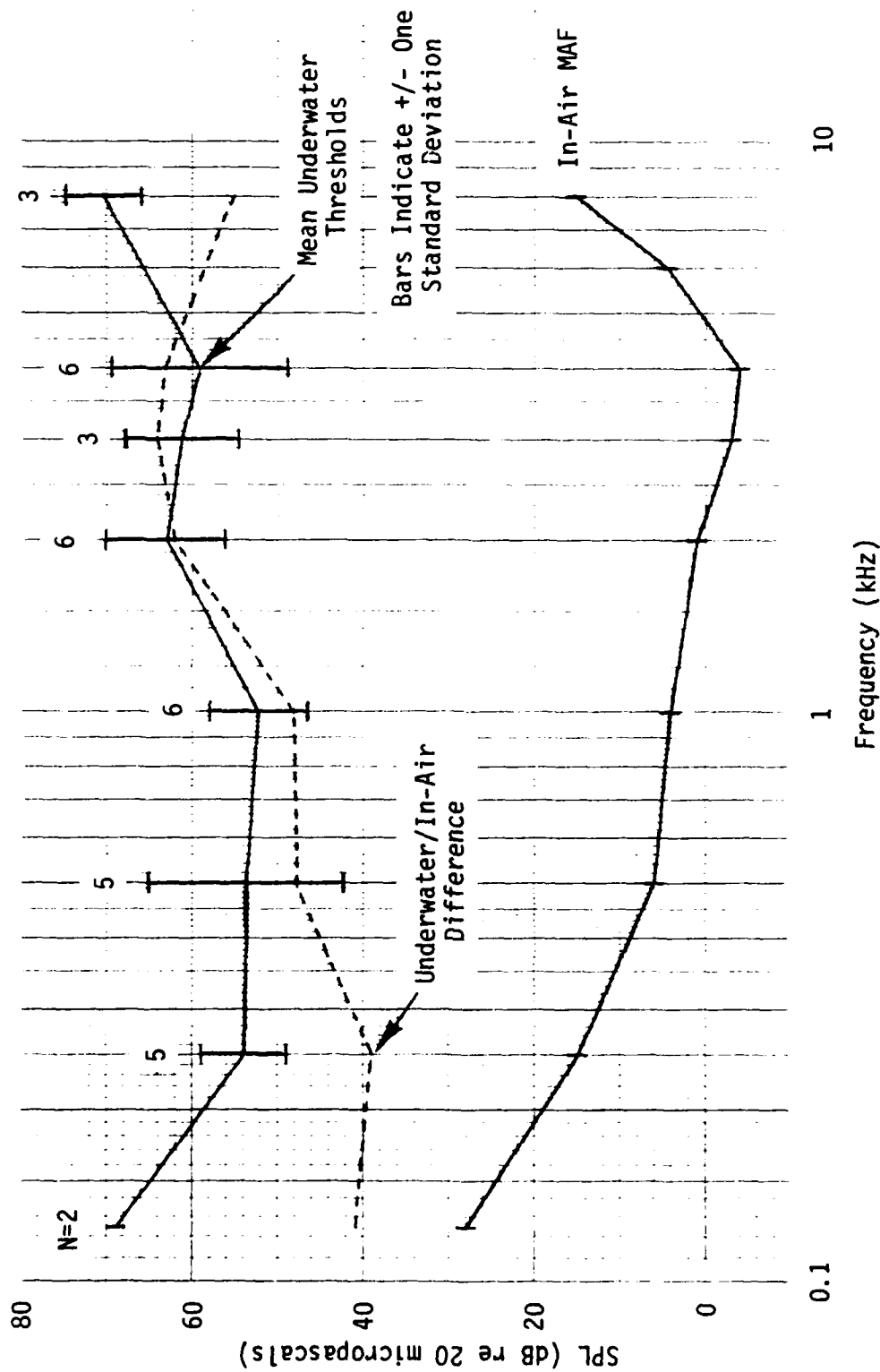


Figure 5-31

Overall mean of the corrected underwater thresholds of audibility for six experiments compared with Killion's (1978) MAF curve; and the difference between underwater and in-air thresholds. The bars indicate ± 1 standard deviation. The number of experiments for which data were available at each frequency is given above each bar.

1000 Hz in Smith's data, as well as the single data point at 6 kHz, represent only one experiment. Except for the aforementioned outlier in Smith's data at 500 Hz, and Hollien's data point at 4000 Hz which may have been influenced somewhat by the outlier appearing at that frequency in Hollien's first experiment, the three independent average curves are quite similar in shape. Hamilton's curve is displaced downward from the other two which could be due to systematic biases introduced by factors such as instrumentation calibration differences in any of the experiments.

The mean underwater threshold curves shown in either Figure 5-31 or Figure 5-32 may be representative of underwater hearing for normal young adult ears and could be used as a basis for relating in-air permissible noise exposure limits to the underwater environment. The curves were derived from the experiments of three independent investigators and involved a sample of at least 20 different subjects (the sample size over all experiments was no doubt greater than 20 but it is not known which or how many subjects may have been duplicates in the repeat experiments.) However, it will be shown in Section 7 of this report, which discusses some suprathreshold measurements, that these threshold data still may not be fully representative of the differences between underwater and in-air hearing.

The reader is reminded that certain assumptions have been made regarding the conversion of Hollien's audiometric data to equivalent in-air SPL (MAF) data, and which *audiometric standards* were being used by both Smith and Hollien. If Smith and/or Hollien did not use the standards of ASA Z24.5-1951 as assumed, but rather used the standards of ISO Recommendation 389-1964 as suggested for all audiometry by Davis and Kranz in 1964 (see Section 4.6), then the agreement between the underwater thresholds of Hamilton, Hollien, and Smith would be much poorer. For example, the curve shown in Figure 5-32 for Smith would move upward away from Hamilton's data by the amounts given in Table 4-2--i.e., 6 to 15 dB, depending upon frequency. (A similar simple adjustment to Hollien's data would not suffice since the choice of the audiometric standard was also involved in the assumptions made regarding his conversion of audiometric data to equivalent MAF data.)

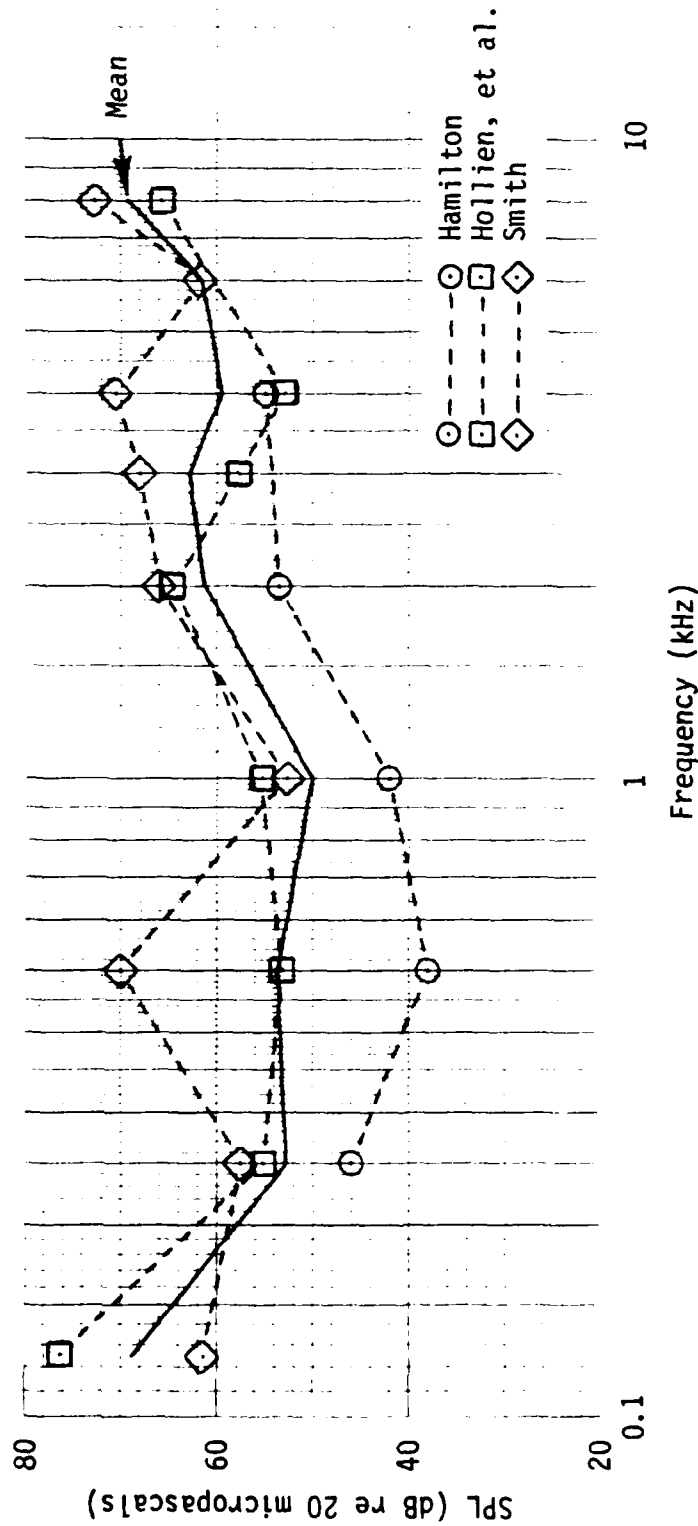


Figure 5-32

Average corrected underwater thresholds of audibility over all experiments conducted by each of three investigators, and the overall mean based upon treating each experimental group as an independent data point (Hamilton - one experiment, Hollien - three experiments, Smith - two experiments). Note that the single data point at six kHz is from only a single experiment by one investigator and, therefore, does not represent a realistic average.

5.10.3 An Average Curve for Underwater Thresholds of Audibility

The solid smooth curve shown in Figure 5-33 represents a best estimate of underwater thresholds of audibility for young listeners with normal hearing based upon the mean data shown in Table 5-17 and Figure 5-31, except that the two outliers previously discussed have been excluded from the calculation of the mean values at 500 Hz and 4000 Hz (this changed the mean values at these two frequencies by about -4 dB and +3 dB respectively). Hamilton's data are also shown in Figure 5-33. If the average smooth curve is shifted downward by about 9-1/2 dB (the dashed curve in the figure), then Hamilton's data tracks very well with the shifted curve--i.e., less than about a 2-1/2 dB difference over all frequencies. (The measurements from Hamilton's experiment, of course contributed to the calculation of the mean values and thus to the shape of the average curve. However, his data set represented only one in a sample size of six data sets.) As has been mentioned previously, the downward displacement of Hamilton's data might be explained by calibration (or other--e.g., background noise) differences between the various experiments. If one wishes to take a more conservative approach to defining the differences between in-air and underwater hearing, one might use the dashed curve in Figure 5-33 as the basic reference pending the acquisition of additional experimental data. However, in Section 7, differences based upon these threshold data will be compared with differences obtained from certain suprathreshold (sound levels well above threshold) experiments in an effort to establish the true relationship between underwater and in-air hearing.

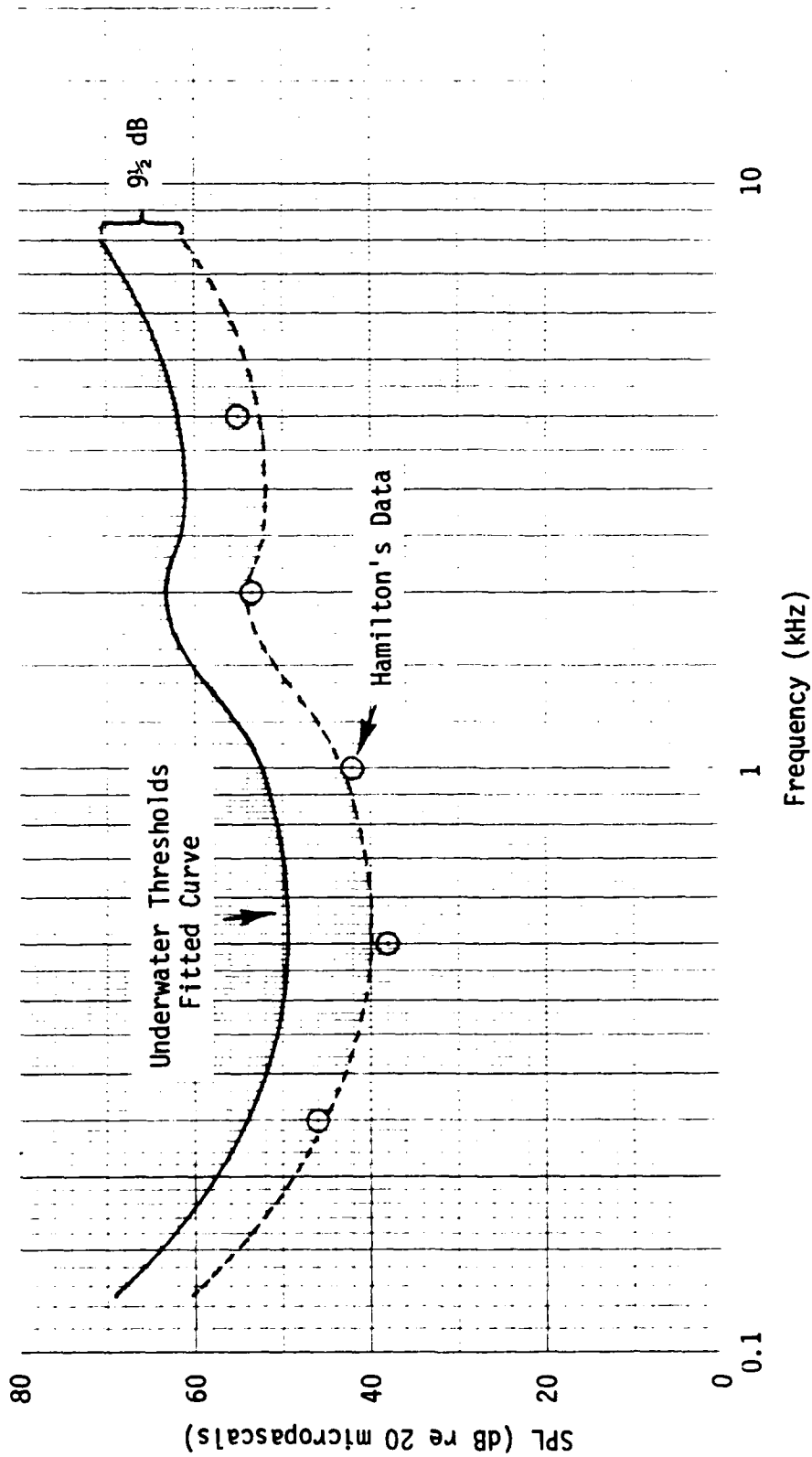


Figure 5-33

Corrected underwater thresholds of audibility: Curve fitted to the data of Hamilton, Hollien, and Smith after rejecting one outlier at 500 Hz and one at 4000 Hz (solid curve); fitted curve shifted downward about 9½ dB (dashed curve); Hamilton's corrected data (open circles) which show excellent agreement with the shape of the fitted curve. The displacement of Hamilton's data suggests a calibration problem between the three experimental data sets.

6. HEARING PROTECTION PROVIDED BY DIVERS' HOODS

6.1 Hood Attenuation as Determined by Measurements of Threshold Differences Using Divers With and Without Hoods

At least four investigators have performed threshold experiments involving measurements of the attenuating properties of divers' hoods: Montague and Strickland (1961), Smith (1969), Norman, Phelps, and Wightman (1971), and Hollien and Feinstein (1975). Three of the experiments have already been discussed elsewhere in this report and the resulting data presented as Figures 5-15, 5-22, and 5-28. In this section we will introduce the data from the fourth experiment--i.e., Norman, Phelps, and Wightman--and will summarize the results of all of the measurements.

Norman *et al.* (1971) made measurements of the attenuating properties of hoods as part of an investigation of the relative roles of bone conduction and tympanic conduction in underwater hearing. The work was done using three subjects in a "home swimming pool." Each subject sat in a weighted chair positioned in the deepest part of the pool (8-1/2 ft deep). Sound was introduced into the water in the form of pulsed tones from an in-air speaker which was placed face down on a plexiglass viewing box at the surface over the diver's head, covered by a cardboard box and a towel, and weighted by two bricks. Each subject wore "a standard face mask (covering eyes and nose) and a single hose regulator." Measurements were made under the conditions of a bare head, full hood, hood with cut outs at the ears, and ear patches only (no hood). The materials were described as follows:

"The hoods were standard full hoods with interior nylon lining. One was of 3/8-in. neoprene foam, the other 1/4 in. The ear holes were ovals about 2-1/4 in. x 1-1/4 in. The ear patches were made of 1/4-in. foam, unlined. They were D shaped, with outer dimensions about 3-1/4 in. x 2-1/2 in. They were constructed of three pieces of rubber stacked on top of one another and cut in such a way as to form a glovelike covering for the ear. The pieces were fastened together with wet-suit cement and held to the head with a horizontal (and in one case, vertical) strap around the head."

The authors did not distinguish between tests conducted with 3/8-in. hoods and those conducted with 1/4-in. hoods. Although a box-shaped swimming pool would provide a standing-wave environment and there was no evidence that in-water sound pressure measurements were made, the authors did point out that "All comparisons of threshold values are from dives in a single session, so that any variation in signal level resulting from different placements of the loudspeaker in the pool or on the plexiglass is not important."

Norman *et al.* presented only the results for the conditions of the hood with ear holes and the ear patches--however, they did indicate little difference between the full-hood and hood-with-ear-holes conditions. Their results are given in Table 6-1.

The results obtained by the four different experimental teams are summarized in Table 6-2.

The attenuation values given in Table 6-2 are also plotted in Figure 6-1. The results from the two experiments using 3/16-in. hoods are plotted with solid lines between the data points, and the results from the two experiments using thicker hood materials--i.e., 3/8- or 1/4-in. thicknesses--are plotted with the dashed lines. On the basis of these data, it appears that the thicker hood materials may provide somewhat greater attenuation on the average than the thinner materials, although the evidence is not conclusive. Overall, there appears to be little attenuation at a frequency of 250 Hz but there is greater than 15 dB attenuation at frequencies of 1 kHz and above.

6.2 Hood Attenuation as Determined by Covering a Hydrophone With a Hood or Hood Material

Another approach to determining the sound attenuation properties of divers' hoods has involved the covering of a hydrophone with a hood or with hood material and measuring the difference in receiving response when compared with the uncovered condition.

Bogert (1964) wrapped an AN/BQR-7 sonar hydrophone in a diving hood of Neoprene rubber and made differential measurements at several frequencies. His attenuation values are plotted in Figure 6-2. According to Smith (1969), Bogert did not specify the thickness of the hood material. (Note: Bogert's original memo of 1964 was not available to us. His data, shown in Figure 6-2, were obtained from Smith, 1969.)

Table 6-1. Attenuation, relative to bare head condition, of divers' hoods (with ear holes) and attenuation provided by ear patches only. (Data from Norman, Phelps, and Wightman, 1971.)

<u>Frequency (Hz)</u>	<u>Hood With Ear Holes (dB)</u>	<u>Ear Patches (dB)</u>
250	4	2
1000	30	4
2000	37	7
4000	(>30)	---

Note: The value in parentheses at 4000 Hz was described as a "preliminary point."

Table 6-2. Attenuation in dB of divers' hoods as determined by four different experimental teams.

Investigators	Hood Thickness	No. of Subjects	Frequency (Hz)							
			250	500	1000	1500	2000	3000	4000	6000 8000
Montague and Strickland (1961)	3/16-in. ¹	7	-2.0	1.0	19.0	24.0	33.0	26.0	28.0	20.5 ----
Smith (1969)	3/8-in.	3 or more ²	----	---	26.5	----	30.0	25.0	26.0	33.5 32.5
Norman, Phelps, and Wightman (1971)	1/4-in. and 3/8-in. ³	3	4.0	---	30.0	----	37.0	----	(>30.0)	----
Hollien and Feinstein (1975) ⁴	3/16-in.	7	-1.6	3.7	16.9	----	----	----	17.7	---- 18.9

¹Montague and Strickland indicated that similar results were obtained for 1/8-in. and 1/4-in. hoods, however, the data were not presented.

²It was unclear as to the number of subjects used in this portion of Smith's experiment.

³Norman, et al. did not distinguish between data taken with the two hood thicknesses.

⁴These attenuation values were calculated from Table I of the reference. It is noted that a mislabeling exists in either Table I or Figure 3 of the reference regarding "hood" and "hood with ear holes" conditions. The differences are small and not significant in this discussion.

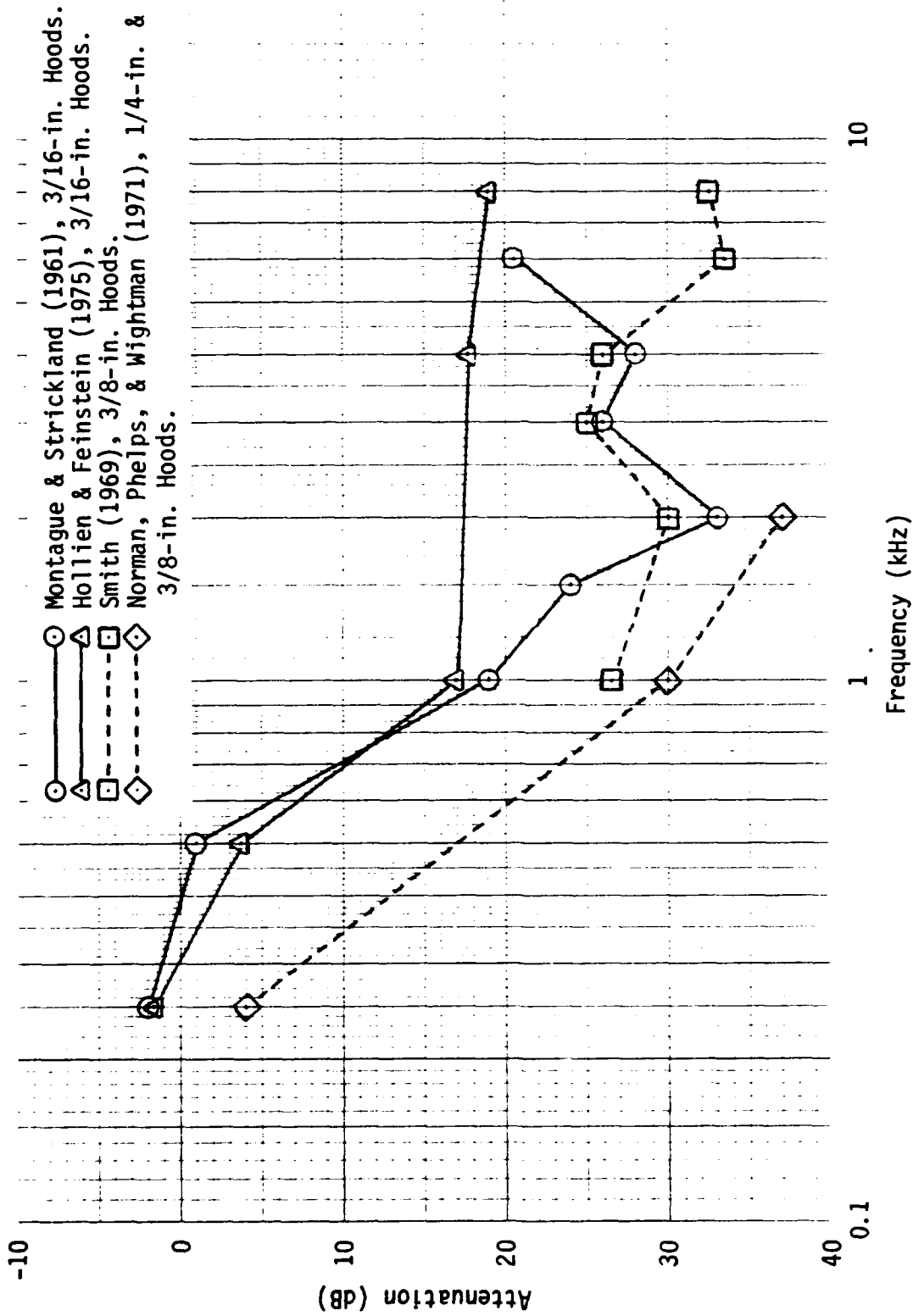


Figure 6-1

Sound attenuation provided by divers' hoods as determined by various investigators.

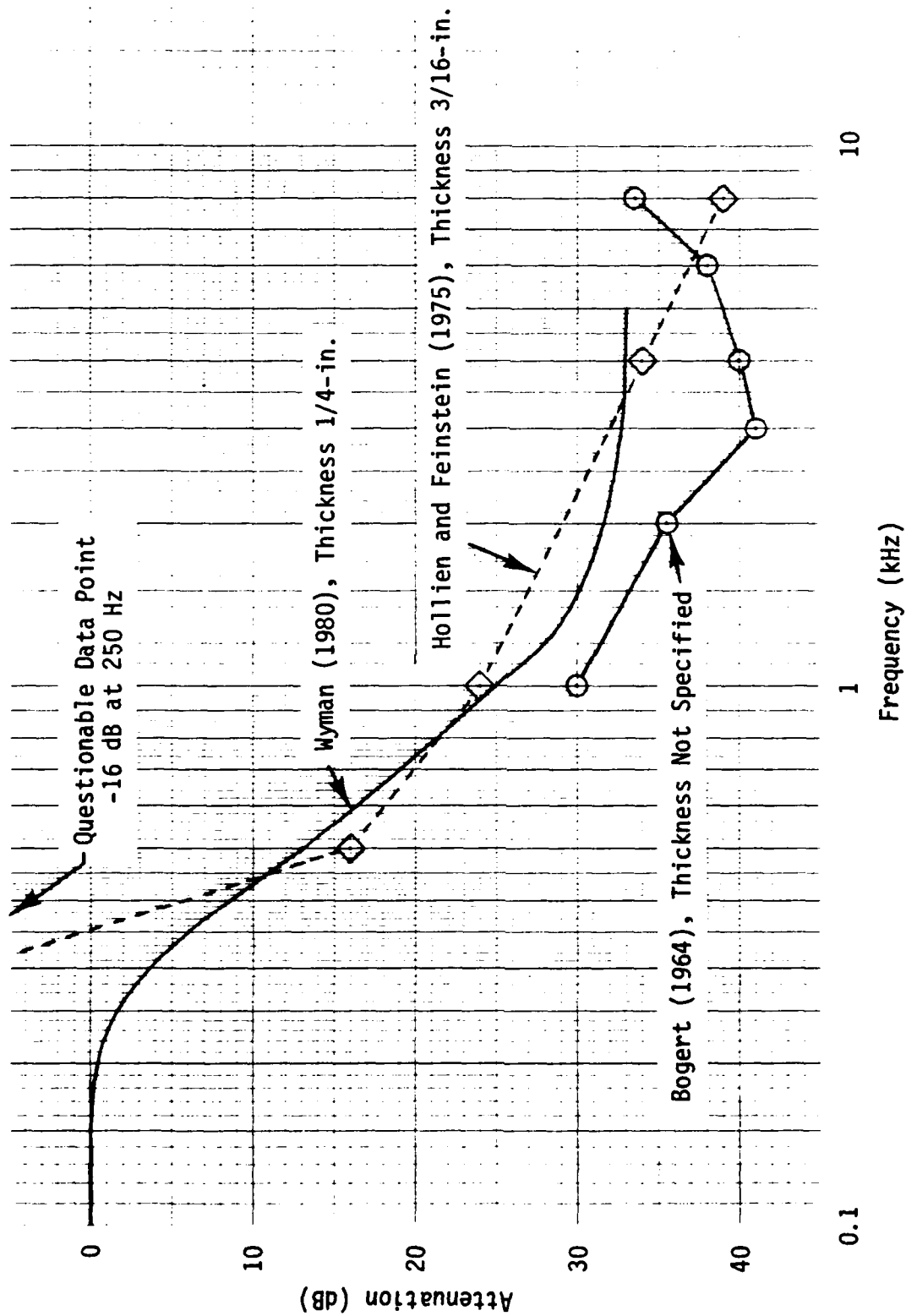


Figure 6-2

Sound attenuation provided by divers' hoods as determined by covering a hydrophone with hood or hood material. (Tones were used by Bogert and by Hollien and Feinstein. Wyman used third-octave-bandwidth analysis of underwater noise produced by a Cavitjet cleaning tool.)

Hollien and Feinstein (1975), in addition to measuring underwater thresholds of audibility, measured changes in sensitivity of an F-36 reference hydrophone when covered with a boot made of the same 3/16-in. Neoprene material used in divers' hoods. Their data are also plotted in Figure 6-2. The data point at 250 Hz (-16 dB) is anomalous since it indicates a large increase in sensitivity rather than a loss; however, the rest of the data track reasonably well with Bogert's values. (It is noted that there were several errors in the presentation of underwater threshold data for divers in Hollien and Feinstein's article. These included the reversal of labels in their Table I versus their Figure 3, both of which were presenting underwater thresholds for seven listeners, and some disagreement in threshold difference values between their Table I and Table II, the latter of which was comparing hood attenuation values for the covered-hydrophone versus hooded-diver experiments.)

Wyman (1980) conducted third-octave-bandwidth analysis of noise produced by Cavijet models 1-A and 1-B cleaning tools both under laboratory conditions and while cleaning ship propellers. As part of these experiments, sound pressure measurements were made with and without a 1/4-in. thick Neoprene wet suit hood covering the hydrophone. Both neoprene and nylon-covered neoprene hood materials were used and produced the same attenuation. Wyman's "smooth" attenuation curve, which was presented in Figure 3 of his report, has been reproduced in our Figure 6-2 for comparison with the data sets of the other investigators. His curve tracks reasonably well with the data of Hollien and Feinstein and the data of Bogert. (It is our interpretation that Wyman's curve was based upon the differences between third-octave-band spectra derived from "measurements taken with and without wet suit hoods over the hydrophone... ." In his report, however, Wyman showed only the spectra for the hood-covered-hydrophone condition and not for the bare-hydrophone condition. His smooth attenuation curve tracks reasonably well with the observed fall-off in his spectra between 200 and 5000 Hz suggesting that the Cavijet's bare-hydrophone spectra were reasonably flat over this frequency range.)

6.3 The Effect of Depth on Hood Attenuation

In experiments using human subjects, Montague and Strickland (1961) conducted their measurements in a fresh water lake with the diver's head at a depth of 3.9 m; Norman *et al.* (1971) performed their tests using divers sitting at the bottom of a swimming pool having a maximum depth of 8-1/2 ft; and Hollien and Feinstein (1975) used a fresh water spring with the divers at a depth of 30 ft.

Smith (1969) conducted the only experiment intended to measure hood attenuation as a function of depth. He performed his tests in the Escape Training Tank of the Navy Submarine School, however, background noise proved to be excessive for valid hood-off measurements even when all non-essential tank machinery was secured. Measurements using two divers were attempted at depths of 33, 66, and 99 ft. The hoods used were of 3/8-in. nylon-lined neoprene. "Inadvertently, one diver did not remove his hood at 66 feet. The other kept his on during both runs at 66 feet. Consequently, data (were) available only for 33 and 99 foot depths." Smith did not present these data in his report, however, he did indicate that the thresholds "with hoods in place were approximately the same at 1 and 4 kHz for these two divers as their thresholds with hoods measured at Millstone Pond at a 15 foot depth." He also indicated that the "difference in thresholds with and without hood were smaller than differences obtained at Millstone Pond but were approximately the same at both the 33 and 99 foot depths." (The smaller differences were probably caused by the background noise problem.) Smith measured differences of only 5 to 10 dB at 250 Hz at both depths. On the basis of this experiment, one can conclude that (3/8-in.) hood attenuation does not change significantly for depths up to 99 feet and as Smith states, "....such hoods are very good analogs of ear muffs used in noisy environments in air."

With regard to those experiments in which a hydrophone was covered with a hood or with hood material: a depth was not given for Bogert's (1964) work; Hollien and Feinstein (1975) also did not indicate a depth value for their covered-hydrophone measurements; and, finally, Wyman (1980) did not specify depths for his Cavijet tests, although two of the events involved cleaning of ship propellers and, therefore, depths would not have been greater than the deepest part of the propeller on each ship (in one case a submarine and in the other case a Navy salvage ship). We would guess that most of the covered-hydrophone experiments were conducted at relatively shallow depths--e.g., less than 30 ft.

6.4 Conclusions and Recommendations Related to the Protective Nature of Divers' Hoods

Sufficient evidence exists to show that for depths up to at least 30 ft divers' hoods offer a significant amount of acoustic protection at frequencies of 1000 Hz and above, and little or no protection at frequencies of 250 Hz and below. The growth function

between these two frequencies is not exactly defined and could depend upon factors such as hood thickness. Hood thickness may also be a determining factor in the *amount* of attenuation provided (i.e., at 1 kHz and above).

Smith (1969) is the only investigator who has attempted to make measurements at depths greater than 30 ft. He went from 33 ft to 99 ft and found indications of no change in the attenuation properties of 3/8-in. hoods. The results of this experiment were somewhat uncertain, however, because of background noise problems (for the no-hood threshold measurements), the use of only two subjects, and the lack of valid data at the intermediate depth of 66 ft. Further, as indicated earlier, the actual data were not presented in Smith's report. Because of these uncertainties and the sparsity of data related to depth effects, we would recommend that additional experimentation be done to strengthen this area. It might be sufficient to use the covered hydrophone approach which would not require the use of human subjects. A transmitter and receiving hydrophone could be mounted on simple rigid framework and lowered to various depths in an open body of water. The hydrophone would be covered with the diver's hood. Various thicknesses would be tested over the audio frequency range. Sound levels well above ambient noise would be used.

Assuming that the recommended additional experimentation shows that the attenuation provided by divers' hoods does not change significantly for depths up to 100 ft, then we would recommend that they be considered acceptable as hearing protection devices for divers working at these depths. One or more "standard" hoods could be approved for Navy use. The selected hoods should provide maximum coverage of the head since underwater hearing is primarily via the bone conduction route. Obviously, the hood should be in good condition and should fit properly (not loose). A minimum hood thickness of 3/16-in. should probably be specified at this time based upon existing data. A face mask *which minimizes facial exposure* should also be used.

If an average curve were to be drawn through the attenuation data of Figure 6-1, an overall mean attenuation value of slightly greater than 25 dB would be obtained for frequencies above 1 kHz. To be conservative in estimating the effect of hood attenuation for divers using noisy underwater tools, one could assume only a 20 dB loss above 1 kHz, and zero loss below 1 kHz. The overall reduction in the unweighted sound pressure level then would be about 10 dB *if* the tool produced *white* noise over the frequency range of 0 to 10 kHz. The beneficial effect for any real tool would depend of course upon its actual spectrum. It is noted that the use of a hood will help protect the ear in the mid frequency range that is most important to maintaining speech intelligibility in air.

Elsewhere in this report we have described a new experimental approach to establishing the differences between in-air and underwater hearing by making use of the naturally occurring *acoustic reflex* as an indicator of comparable sensation levels in the two mediums. The acoustic reflex phenomenon could also be used to measure hood attenuation characteristics (at sound levels well above threshold). The activation of the acoustic reflex would be sensed for divers with and without hoods. For the hooded condition, the reflex probe could be inserted into the ear at the surface of the water through a small cut out in the hood at the ear location (Norman *et al.*, 1971, and Hollien and Feinstein, 1975, have shown that ear holes make practically no difference in underwater hearing sensitivity for the hood-on case; however, this is immaterial anyway since the probed ear would be just above the surface of the water). Various types and thicknesses of hoods as well as various face masks could be tested using this approach.

Because of the wide disparity between the results of the many underwater threshold experiments, as discussed in Section 5 of this report, there is some suspicion that many of the bareheaded measurements may have been contaminated by low-level background noise. Masking effects, therefore, might cause the underwater thresholds to be fictitiously high for the hood-off condition but not for the hood-on condition (the signal-to-noise ratio would be significantly better for the hood-on case because the hood would attenuate the *noise* at 1 kHz and above while the signal level would have to be increased to overcome the hood attenuation and again reach the threshold of audibility at the cochlea). As a consequence of noise contamination, the measured hood attenuation values may have been too low in some of the underwater threshold experiments. The use of the acoustic reflex approach, at sound levels well above background noise, would help to answer this question.

7. COMPARISON OF IN-AIR AND UNDERWATER HEARING AT SUPRATHRESHOLD SOUND LEVELS -- DEMONSTRATION TESTS OF TWO APPROACHES

7.1 Introduction

In previous sections of this report we have pointed out the problems associated with accurately measuring underwater thresholds of audibility. It is difficult to find an underwater environment that approximates free-field conditions but is sufficiently *quiet* to avoid contamination by unwanted noise. Background noise can easily mask the low-level signals that the subjects are trying to hear, and this can result in fictitiously high underwater audibility threshold levels. Further, it is not yet clear that the differences between underwater and in-air hearing are the same at threshold values as they are at higher levels of sound.

To overcome these difficulties, it would be desirable to make comparisons at sound levels well above threshold (i.e., at *suprathreshold* levels). Smith *et al.* (1970 and 1985) have tried the approach of determining sound pressure levels in water and in air that produce equal amounts of *temporary threshold shift* (TTS).^{*} Unfortunately, the amount of TTS for any given set of exposure conditions can vary significantly from subject to subject. Harris (1979) presents data (Figure 9.11 in the reference) which show a spread of over 30 dB for nine subjects exposed (in air) for 24 hours to an octave band of noise centered at 4000 Hz at a sound pressure level of 85 dB. The so-called *tough-eared* subject may exhibit no TTS while the *tender-eared* subject may have a large TTS under the same exposure conditions. Because of such wide variability, a large sample size is probably necessary to obtain accurate comparisons in a statistical sense between underwater and in-air hearing using the TTS approach. It is also preferable for this method to use the same subjects for both in-water and in-air measurements (Smith, 1970, used

^{*}Persons exposed to loud noise for a sufficient period of time may experience shifts in their thresholds of audibility in the direction of poorer hearing; i.e., higher thresholds. If the shifts are temporary in nature, they are called *temporary threshold shifts*--also referred to as *auditory fatigue*. TTS will increase with increased sound pressure levels and increased exposure times and may eventually result in *noise-induced permanent threshold shift*, or NIPTS. The amount of TTS will also depend upon factors such as the frequency spectrum and temporal pattern of the exposure. TTS may typically be encountered at octave-band sound pressure levels of 70-75 dB and above. The amount of TTS can vary significantly from individual to individual for a given set of exposure conditions.

different subjects; six for the in-water tests and five other subjects for the in-air measurements). Another disadvantage of this approach is that the experimental phase can be quite time consuming. The status of hearing (i.e., thresholds of audibility) for each subject must be established before exposure (i.e., by audiometry). The subject must then be exposed to the selected noise type (frequency, level, temporal pattern, time of exposure, etc.) in the water medium and then be moved quickly to an audiometric booth for post-exposure measurements to obtain TTS values. Comparable TTS values in the other medium (air) must be found and this may necessitate trial-and-error bracketing using various sound levels. All TTS measurements have to be made *one at a time* after each exposure and, for a large number of subjects and frequencies, the procedure can proceed very slowly.

We have considered two other approaches for comparing in-air and underwater hearing at suprathreshold sound levels and have conducted a brief demonstration experiment to see if the concepts are viable. One approach involves the determination of *equal loudness levels* in air and in water, and the other involves measurements of *acoustic reflex thresholds* (ART) and acoustic reflex growth in the two media. Each of these concepts and the demonstration experiment will be described.

7.2 Description of the Proposed Methods

7.2.1 Equal Loudness Comparisons

In considering the desirability of establishing the relationship between in-water and in-air hearing at sound levels nearer those encountered in normal working environments and well above low level background noise in quiet environments, the idea of performing equal loudness comparative tests appeared promising. The concept would involve placing a swimmer on his or her side in water and at the surface, with one ear (and most of the skull) underwater and the other ear projecting just out of the water. The underwater ear (and skull) would be stimulated with pulses of sound (tones) from an underwater transducer placed below the swimmer. The above-water ear would be stimulated alternately with pulses of the same frequency from an in-air loudspeaker placed above the swimmer. One of the sound levels would be raised or lowered as directed by the subject to match the other fixed sound level. Various levels and frequencies would be used, the swimmer's ear positions would be switched, the contents of the ear canal would be varied (air versus water), and a number of subjects would be used to obtain statistically significant data.

Equal loudness comparisons may tend to exhibit somewhat poor repeatability--i.e., a large data spread--because they require judgment calls. The problem can be exacerbated if there are any unwanted conditions such as noticeable background noise differences (air noise versus water noise), signal distortions, etc.--these need to be controlled or eliminated. Such an experiment probably would require a moderately large sample size--e.g., say a minimum of ten--in order to obtain valid comparative data. However, the subjects need not be trained divers.

Sound levels at the head position in air and in water would be measured (i.e., probed) with appropriate equipment such as sound level meters in air and reference hydrophones in water. Because of the presence of the water surface, and possibly other boundaries such as the bottom or sides of a pool, standing wave patterns would exist and therefore probing of the sound field would be essential for determining actual sound pressures in the vicinity of the subject's head. Figure 7-1 illustrates the experimental setup for conducting an equal-loudness test in a swimming pool.

7.2.2 Acoustic Reflex Comparisons

This concept would take advantage of the naturally occurring *acoustic reflex*; i.e., the activation of the muscles of the middle ear when the ear is subjected to loud sounds, which serves as a protective mechanism. It is an interesting fact that stimulation of only one ear will elicit the response in both ears. Thus, by stimulating the underwater ear of our swimmer in Figure 7-1, we can observe the reflex in the above water ear using a probe that detects impedance changes at the eardrum.* If we measure the sound level for reflex activation in water and compare it to an equivalent air activation level measured before or after the in-water test, we have a direct comparison of in-water to in-air hearing performance at sound pressure levels on the order of 70 to 100 dB (in air); again well above threshold values and in the region of interest. Further, if we systematically increase the sound level at each frequency, we can obtain relative measures of reflex growth which may be extremely important for establishing correct trading relationships

*The underwater stimulation is probably *binaural* because of bone conduction. This suggests the need in future experimental work to compare reflex thresholds for binaural *in-air* sounds; and perhaps for unilaterally deaf subjects in both air and water.

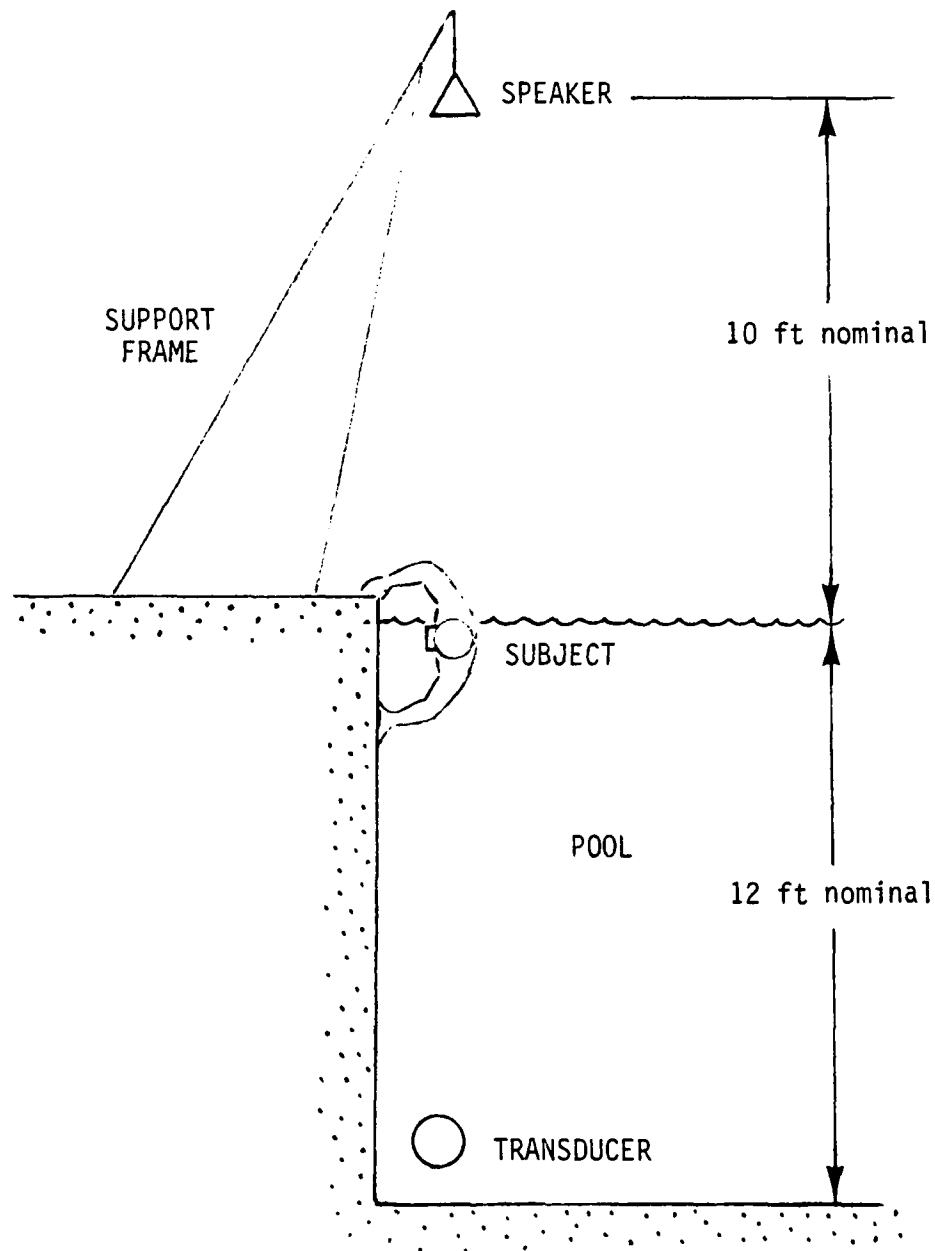


Figure 7-1

Experimental setup for conducting an equal loudness test or an acoustic reflex test. (The in-air loudspeaker is not used in the acoustic reflex test.)

for calculating permissible exposure times. (If underwater hearing is primarily by bone conduction, the reflex will not protect the ear, thus a knowledge of the rate of growth is potentially very important.)

The setup for conducting this experiment in a swimming pool would be the same as that shown in Figure 7-1 except that the in-air speaker would not be used and an acoustic reflex sensor (probe) would be inserted into the above-water ear canal and connected to an otoadmittance meter. The underwater transducer would emit pulsed tones of sufficient length to fully activate the reflex (i.e., >1 sec). The pulses would be repeated at intervals sufficiently long to allow the effect of the reflex to fade away (also >1 sec). As in the case of the equal-loudness test, the underwater sound field would be probed around the subject's head position using a calibrated hydrophone. The experimental parameters again would include frequency, sound level, right or left ear underwater, and air or water in the ear canal. A number of subjects would be tested.

7.3 The Demonstration Tests

A series of tests was conducted to demonstrate the feasibility of these two concepts. It is emphasized that this series did not represent a complete experiment since borrowed in-house equipment was employed, and limited free off-hours time was obtained at one of the University's swimming pools (on a not-to-interfere basis).

The work was performed over the Christmas holiday period. Three days were allotted, from 0700 to 1100 each day. Because of the need to set up and check out the equipment each day (and dismantle it each day for later scheduled swimming sessions), and because of certain noise interference problems particularly on the third day (e.g., pool maintenance), limited data were obtained. No measurements resulting in data were made on the first day--after equipment setup and test, the proposed procedures were tried but time did not permit the collection of actual test data. Partial measurements were made on the second and third day at frequencies of 1, 2, and 4 kHz. Two APL divers with *young* ears served as subjects--K. Kientz and M. Ohmart (note: it is important to provide subjects' names or other unique identifiers when reporting results of such tests in order to judge the *independence* of data in relation to various samples used in prior or subsequent experiments). Only the right ear of each of the divers was positioned under water (the divers' ears were reasonably well matched, however), data were obtained only for the condition of *air in the ear canal*, and there was no opportunity to conduct repeat

measurements.* (Note: The use of APL's acoustic barge in more *open* waters would have been preferable to the use of a swimming pool with its inherent reverberation and standing wave problems. However, local water temperatures are too cold during the winter months for lengthy testing of this type. It would be desirable to conduct a complete experiment using the barge and its instrumentation during the summer time frame.)

A functional diagram showing the arrangement of experimental equipment for the equal loudness tests is presented in Figure 7-2. A similar functional diagram for the acoustic reflex tests is shown in Figure 7-3. Table 7-1 lists the specific equipment used in both experiments.

Signals (tones) were provided by an APL-developed *Low Frequency Acoustic Target Signal Generator* which covers the frequency range of 70 Hz to 10 kHz. For the equal loudness tests, the signals were fed to an electro-mechanical commutative switch which directed them alternately to the amplifier for the underwater transducer and then to the amplifier for the in-air speaker. The signal on-time was about 350 ms and the off-time about 150 ms. Thus the underwater tone would be on for 350 ms and then the in-air tone would be on for 350 ms, with 150 ms gaps between. For the acoustic reflex tests, the commutative switch provided control for alternately turning the underwater signal on and off (no in-air signal was used). The on-time and off-time were both about 2-1/2 sec. These latter times were sufficient to allow the acoustic reflex to be fully activated in the first case and to fade away completely in the second. (Either the in-air signal or the underwater signal was operated in a *continuous* tone mode whenever SPL measurements needed to be made.) A strip chart recorder was connected to the otoadmittance meter in order to provide a permanent record of the impedance changes in the eardrum-ossicular chain produced by the activation of the acoustic reflex.

At the start of the experiment, two calibrated hydrophones were placed in the water without the subject present to probe the sound field. The outputs for both hydrophones were identical when occupying the same positions. After this calibration check,

*The assumption of *air in the ear canal* is based upon the fact that there was no attempt made to flush the ear canal to remove the air pocket. Each diver merely placed the side of his head into the water which probably trapped an air bubble in the canal. This is not an important issue, however, since underwater hearing is primarily by the bone conduction route.

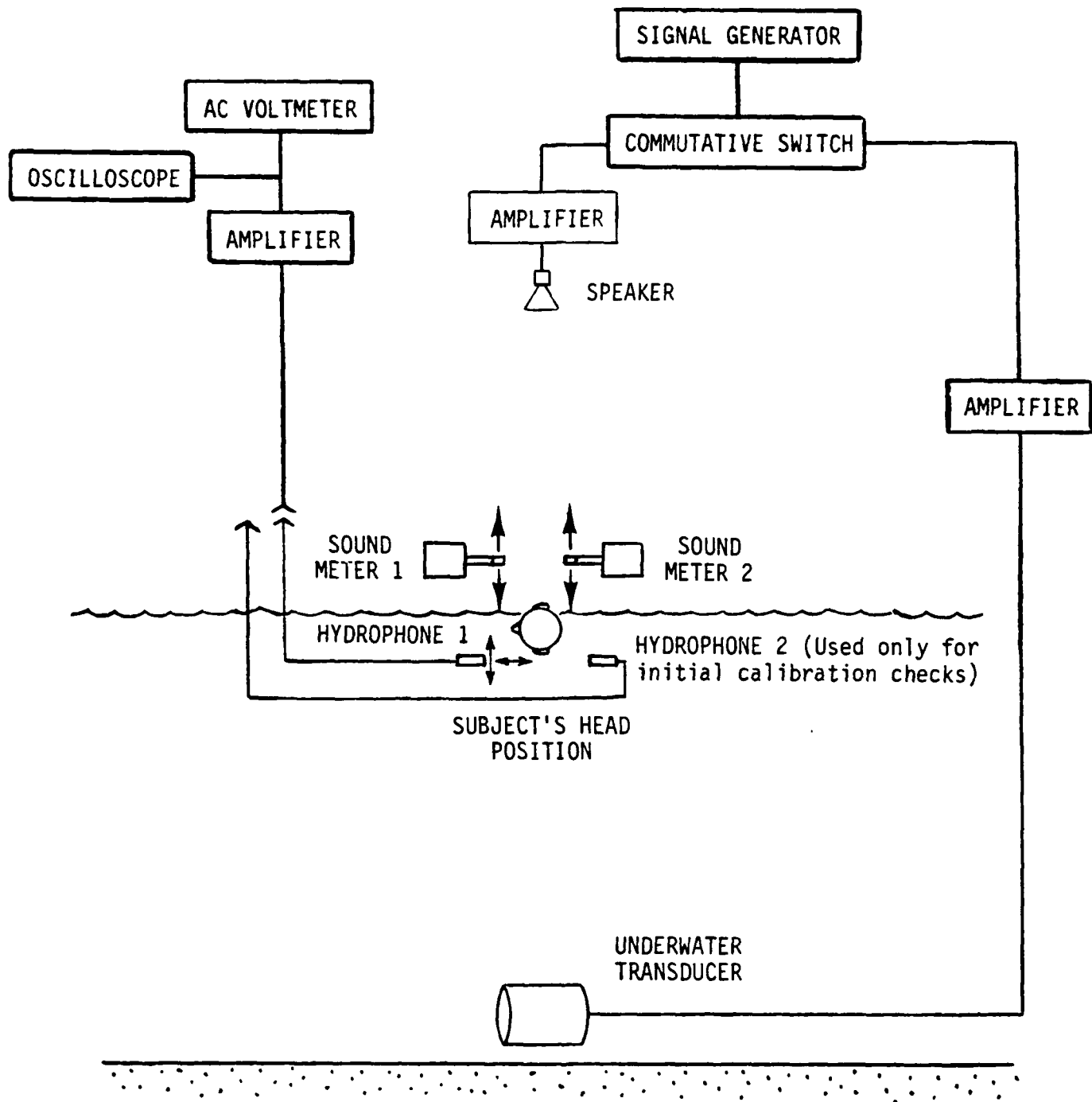


Figure 7-2

Functional diagram for equipment used during equal loudness tests.

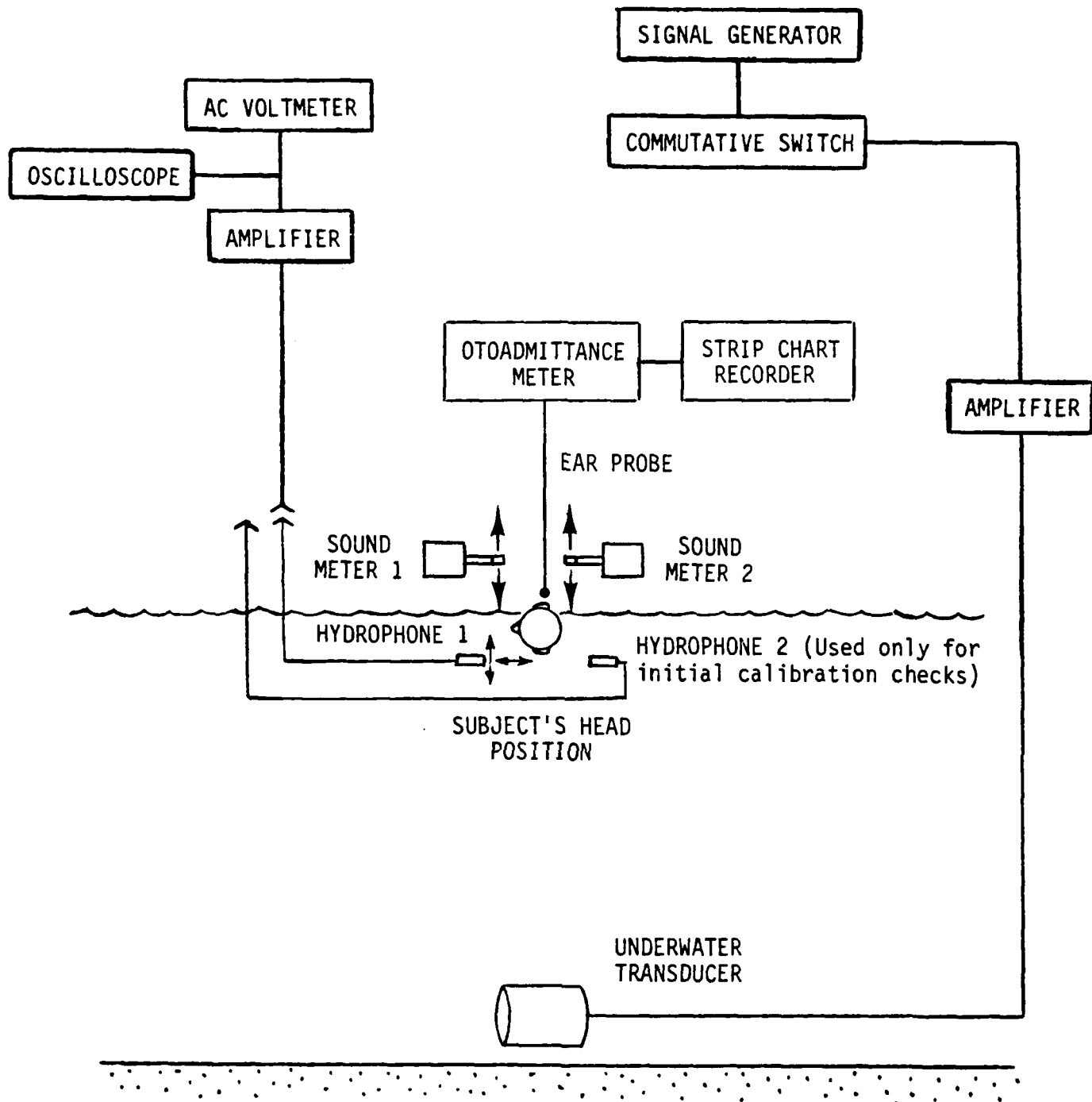


Figure 7-3

Functional diagram for equipment used during acoustic reflex tests.

Table 7-1. Instrumentation used during the equal loudness and acoustic reflex tests.

Air Acoustics Equipment

Signal Generator: APL LOW FREQUENCY ACOUSTIC TARGET SIGNAL GENERATOR, SER. 006

Amplifier: REALISTIC MPA 20 MODEL 32-2020B, SER. 10A82

Speaker: UNIVERSITY SOUND MODEL IB-A8, 30 WATTS, 8 OHMS, SER. 476

Meter 1: GENERAL RADIO SOUND LEVEL METER TYPE 1551-B, SER. 210

Meter 2: GENERAL RADIO PRECISION SOUND-LEVEL METER & ANALYZER TYPE 1933, SER. 3413

Water Acoustics Equipment

Hydrophone 1: BRUEL & KJAER TYPE 8101, SER. 693567

Hydrophone 2: BRUEL & KJAER TYPE 8101, SER. (not recorded)

Signal Generator: APL LOW FREQUENCY ACOUSTIC TARGET SIGNAL GENERATOR, SER. 006 (same instrument as above)

Amplifier: INSTRUMENTS, INC. POWER AMPLIFIER MODEL LDC3-1, SER. 001 (used 12/22/87)
McINTOSH MODEL MC 2300E, SER. 2Y680 (used 12/23/87)

Projector: ITC MODEL 2010, SER. 500

SPL Instrument: AC VOLTMETER, FLUKE MODEL 910, SER. 531
APL-UW HYDROPHONE AMPLIFIERS (2)
OSCILLOSCOPE, TEKTRONICS MODEL 221
STRIP CHART RECORDER, BRUSH MARK 280, MODEL 15-6327-01, SER. 227
OTOADMITTANCE METER, GRASON-STADLER MODEL 1720, SER. 131

Switching Equipment

APL-UW ELECTRO-MECHANICAL COMMUTATIVE SWITCH

only one hydrophone was used for the subsequent tests, however, it was moved around each subject's head to evaluate the sound pressure variations (typically three hydrophone positions were used--in front of the face, behind the head, and just below the ear).

For the equal loudness tests, two different sound level meters were used to probe the in-air sound field just above the surface of the water in the vicinity of the diver's ear. The sound meter microphones were moved up and down as well as horizontally to obtain the best estimates of the sound pressure level at the ear position. The *fast averaging time* was selected on both meters, and measurements were recorded for both *A-weighting* and *no-weighting* operating modes. (Although the A-weighted data were not considered to be necessary, they subsequently proved to be useful in the analysis.)

The two subjects wore wet suits but no hoods, fins, or weight belts. This allowed them to float on their sides at the surface while holding on to the edge of the pool with one hand. The other hand was used either to adjust a *volume control* for the underwater projector during the matching process for the equal loudness tests, or to give hand signals (increase level or decrease level) for one of the experimenters to make the required adjustments.* The free hand was also used to fit and hold the ear probe in position during the acoustic reflex measurements. Each diver wore a small eye-nose mask while holding his breath during the actual measurements.

Table 7-2 lists the equal-loudness tests performed on December 22 and 23. Table 7-3 is a summary of the acoustic reflex tests which were performed on December 23. Again, because of time and facility constraints, it is emphasized that these demonstration tests did not represent a complete series (i.e., all frequencies, both ears, etc.).

Figures 7-4 through 7-7 are photographs of the actual experiment.

*The volume control was used during the early part of the experiment but proved to have too limited a range of adjustment. Hand signals were then used to direct test personnel on the side of the pool to manually increase and decrease the volume until a "match" was obtained. Both ascending and descending adjustments were made in order to bracket the *best* match.

Table 7-2. Summary of equal-loudness tests conducted in the IMA* pool on December 22 and 23, 1987.

<u>Test No.</u>	<u>Subject</u>	<u>Ear In Water</u>	<u>Ear Canal Contents</u>	<u>Freq (kHz)</u>	<u>Date</u>	<u>Range of In-Air SPL, dB (Unweighted)</u>
E.L. 1	Kientz	Right	Air	1	12/22/87	70.5 to 92.25
E.L. 2	Kientz	"	"	2	"	72.0 to 91.5
E.L. 3	Ohmart	"	"	1	"	70.0 to 93.25
E.L. 4	Ohmart	"	"	2	"	72.0 to 98.5
E.L. 5	Ohmart	"	"	4	"	71.0 to 80.0
E.L. 6	Kientz	"	"	4	12/23/87	75.5 to 79.25? (High Back-ground Noise)
E.L. 7	Ohmart	"	"	4	"	78.0 to 94.5

*The Intramural Activities (IMA) swimming pool is located on the eastern side of the University of Washington campus. It is an L-shaped pool having a depth of 12 feet in the diving portion of the "L". The in-air speaker was attached to the 3-meter diving board with the active face of the speaker at a height of 113 inches above the surface of the pool. The depth to the top of the underwater transducer was 123 inches on December 22 and 119 inches on December 23.

Table 7-3. Summary of acoustic reflex tests conducted in the IMA pool on December 23, 1987.

<u>Test No.</u>	<u>Subject</u>	<u>Ear In Water</u>	<u>Ear Canal Contents</u>	<u>Freq (kHz)</u>	<u>In-Water SPL, dB¹</u>	<u>Change In Susceptance, millimhos²</u>
A.R. #1	Kientz	Right	Air	1	130.6	0.4
					131.0	0.8
					137.0	2.2
					141.5	3.2
					143.8	4.0
A.R. #2	Kientz	"	"	2	132.8	jitter
					133.9	0.8
					130.2	0.8
					139.8	4.5
					143.8	4.5
	147.1	4.0				
A.R. #3	Ohmart	"	"	1	135.7	1.7
					146.5	4.0
					(Insufficient time to complete test)	

¹Reflex initiated for both subjects at an underwater SPL in the neighborhood of 130 dB.

²Reflex detected in the above-water contralateral (opposite) ear and measured using Otoadmittance Meter, Grason-Stadler Model 1720 (220 Hz mode) and recorded with Brush (strip chart) Recorder Mark 280, Model 15-6327-01.



Figure 7-4

Underwater sound projector (ITC-2010 transducer) positioned near the pool bottom for the equal loudness and acoustic reflex tests.

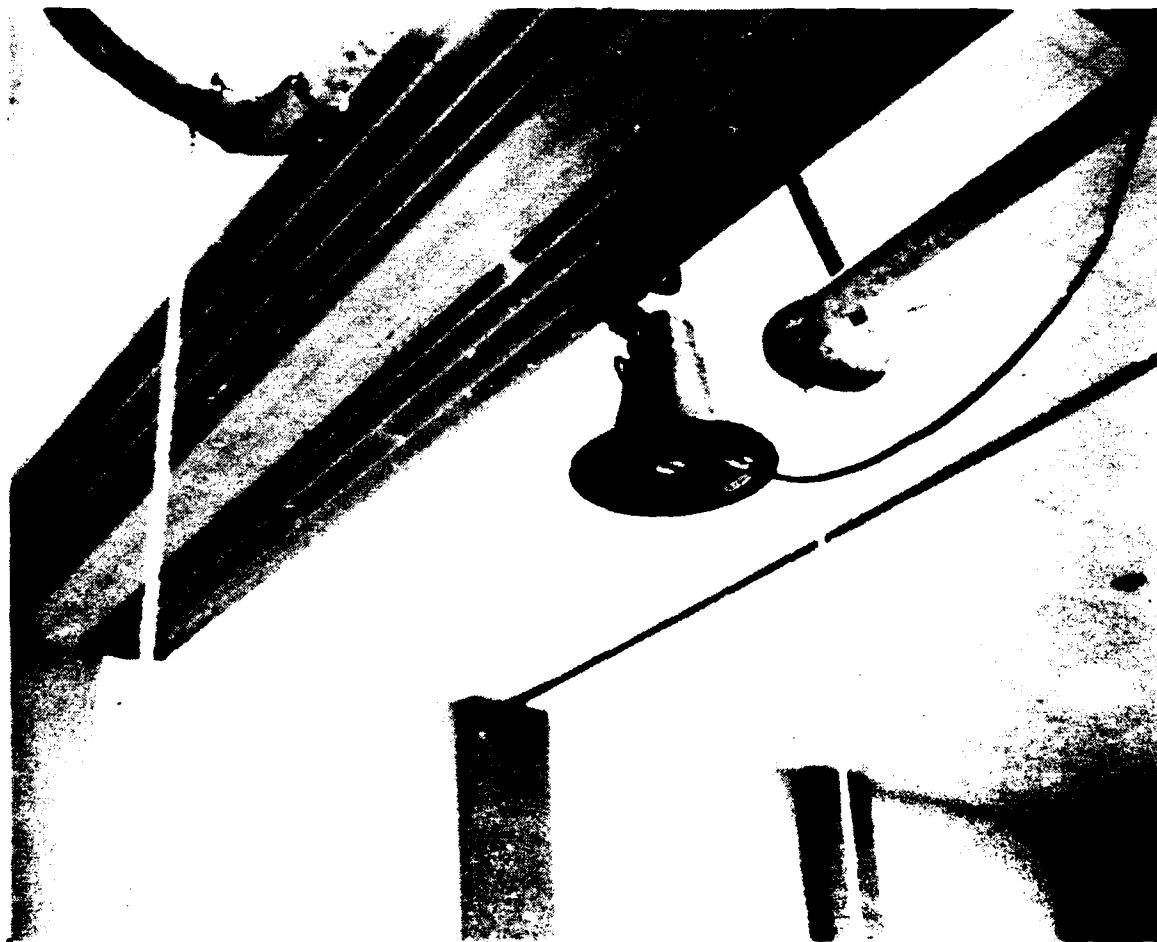


Figure 7-5

In-air loudspeaker mounted on the three-meter diving board directly above the underwater sound projector during the equal loudness tests.

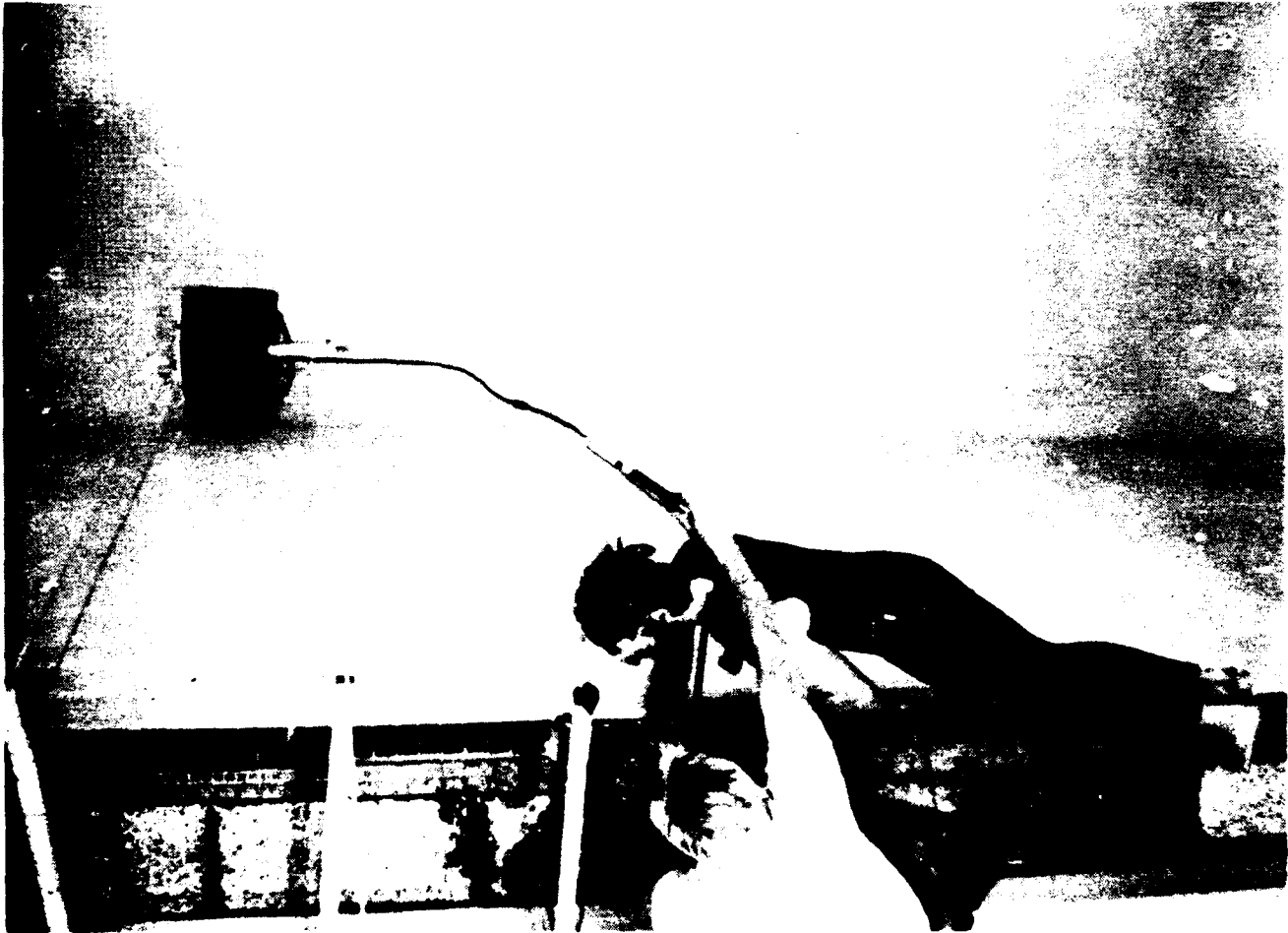


Figure 7-6

Probing the underwater sound field around the subject's head position using a reference hydrophone during the equal loudness tests. The underwater sound projector, an ITC-2010 transducer, is seen to the left of the subject and is at a depth of about 10 ft (as measured to the top of the transducer).

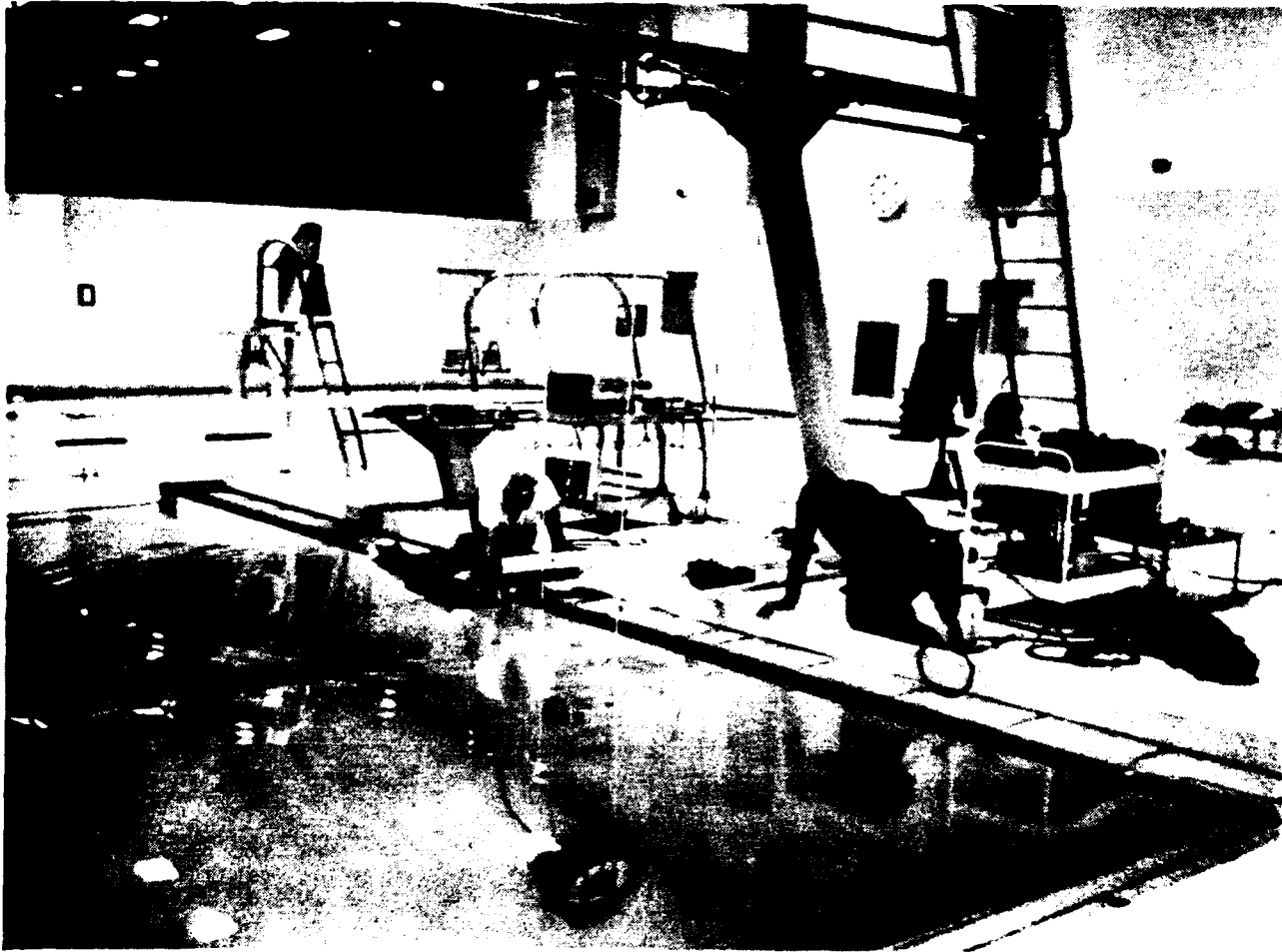


Figure 7-7

Setup for the equal loudness tests. In-air loudspeaker mounted on the three-meter diving board. ITC-2010 transducer near the pool bottom. The sound field is being probed around the diver's head position while instrumentation is being read and recordings made. The same setup was used for the acoustic reflex tests except the in-air speaker was not used and activation of the reflex was detected using an otoadmittance meter.

7.4 In-Air Audiometric Data

Audiometric measurements were made on the two APL divers (Kientz and Ohmart) prior to their participation in the in-water experiments.* These included both audibility threshold measurements and acoustic reflex threshold measurements. The audibility threshold measurements were made to insure that both subjects exhibited reasonably *normal* hearing. The reflex threshold measurements were required to allow the desired comparisons to be made between reflex activation in air and in water.

Figure 7-8 presents the audiometric test results for Kientz, and Figure 7-9 presents the data for Ohmart. (Note that hearing levels were read only to the nearest 5 dB increment in accordance with normal audiometric evaluation procedures.) Both subjects exhibited reasonably good threshold hearing levels in both ears, with the younger Ohmart being on the average about 10 dB *better than* the somewhat older Kientz. Both subjects exhibited contralateral acoustic reflex activation at audiometric levels in the range of 80 to 90 dB for both ears.

7.5 Results of the Experiments

7.5.1 Equal Loudness Test Results

Several problems existed during the conduct of the equal loudness tests which made the results of this portion of the overall experiment somewhat difficult to interpret. It is emphasized, however, that the approach has been demonstrated to be a viable one, and with better control of environmental factors, slight improvement in the equipment, and some minor modifications to the test procedures, tests can be conducted that will result in data providing very useful information over all frequencies of interest. The tests are reasonably easy to conduct provided one has control of the facility.

The problems encountered included: (1) excessive in-air background noise caused by operation of swimming pool machinery and water outflow noise, as well as additional background noise during a pool maintenance period on the last day (12/23) of the experiment; (2) underwater signal distortion during the second day of the experiment (12/22; this was the first day of data taking) caused by a problem with the amplifier

*Audiometric evaluations were performed by Professor Phillip A. Yantis, Associate Chairman, Speech and Hearing Sciences Department, University of Washington.

UNIVERSITY OF WASHINGTON
DEPARTMENT OF SPEECH AND HEARING SCIENCES
SPEECH AND HEARING CLINIC

RECORD OF AUDIOMETRIC EVALUATION

NAME KEN KIENTZ
AGE 34 DATE 11/24/87

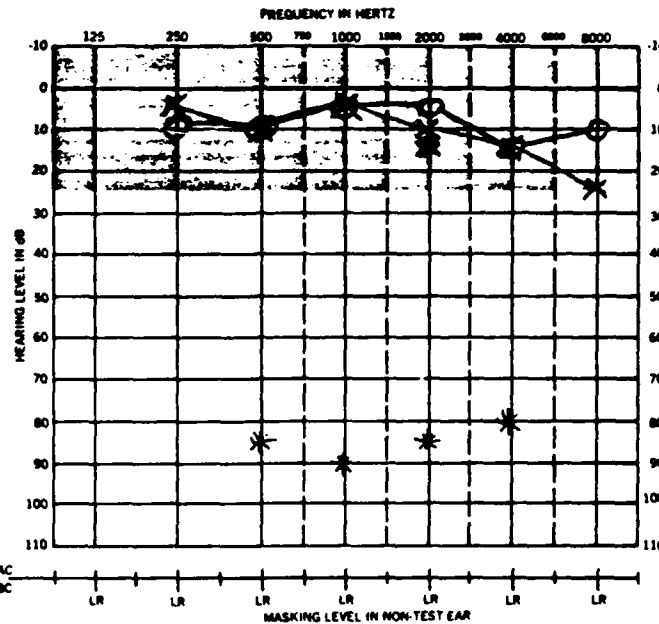
CALIBRATION
CURRENT ANSI REFERENCE
LEVELS FOR PURE TONES
AND SPEECH

ABBREVIATIONS

AC AIR CONDUCTION
BC BONE CONDUCTION
CNE COULD NOT ESTABLISH
DNT DID NOT TEST
EM EFFECTIVE MASKING
HL HEARING LEVEL
MCL MOST COMFORTABLE LEVEL
MLV MONITORED LIVE VOICE
NBN NARROW BAND NOISE
NR NO RESPONSE
SPL SOUND PRESSURE LEVEL
SPN SPEECH NOISE
TD THRESHOLD OF DISCOMFORT
WN WHITE NOISE

RESPONSES

CONSISTENT ☐ INCONSISTENT ☐
RAPID ☐
SLOW ☐
DELAYED ☐



AUDIOGRAM KEY

RIGHT LEFT
AC UNMASKED
AC MASKED
BC MASTOID UNMASKED
BC MASTOID MASKED
BC FOREHEAD MASKED
BC FOREHEAD UNMASKED
SOUND FIELD
EXAMPLE OF NO RESPONSE SYMBOLS

AUDIOMETER

NO.:
MAKE: TELE-DINE
MODEL: TA-2000

SPEECH HEARING LEVELS

		TYPE	SOURCE	NOISE	MCL		TD
RIGHT	HL	SPONDEE THRESHOLD <input type="checkbox"/>	TAPE <input type="checkbox"/>	WN <input type="checkbox"/>	RIGHT	HL	HL
MASKING IN LEFT	HL	DISC <input type="checkbox"/>	DISC <input type="checkbox"/>	SPN <input type="checkbox"/>			
		MLV <input type="checkbox"/>	MLV <input type="checkbox"/>	OTHER <input type="checkbox"/>			
LEFT	HL				LEFT	HL	HL
MASKING IN RIGHT	HL						

SPEECH DISCRIMINATION SCORES

		TEST 1	TEST 2	TEST 3	STIMULI	SOURCE	NOISE	RESPONSE
RIGHT	%	HL	%	HL	W-22 <input type="checkbox"/>	TAPE <input type="checkbox"/>	WN <input type="checkbox"/>	TALK BACK <input type="checkbox"/>
MASKING IN LEFT	HL	LIST	HL	LIST	DISC <input type="checkbox"/>	DISC <input type="checkbox"/>	SPN <input type="checkbox"/>	WRITTEN <input type="checkbox"/>
					OTHER <input type="checkbox"/>	MLV <input type="checkbox"/>	OTHER <input type="checkbox"/>	MULTI-CHOICE <input type="checkbox"/>
LEFT	%	HL	%	HL				
MASKING IN RIGHT	HL	LIST	HL	LIST				

COMMENTS:

PROBE -
LT RT
1000 Hz - 90 90
2000 - 85 55
4000 - 80 80
500 - 55 85

YANTIS

Audiologist

Figure 7-8

Audiometric test results for Ken Kientz. Acoustic reflex thresholds are listed at the bottom of the page and are also plotted as asterisks.

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RECORD OF AUDIOMETRIC EVALUATION

NAME MIKE OHMART
AGE 25 DATE 12/16/87

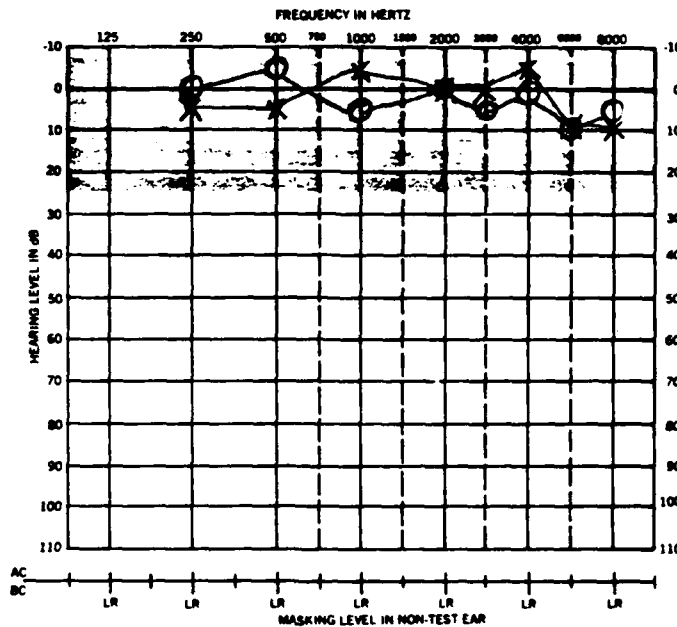
CALIBRATION
CURRENT ANSI REFERENCE
LEVELS FOR PURE TONES
AND SPEECH

ABBREVIATIONS

AC AIR CONDUCTION
BC BONE CONDUCTION
CNE COULD NOT ESTABLISH
DNT DID NOT TEST
EM EFFECTIVE MASKING
HL HEARING LEVEL
MCL MOST COMFORTABLE LEVEL
MLV MONITORED LIVE VOICE
NBN NARROW BAND NOISE
NR NO RESPONSE
SPL SOUND PRESSURE LEVEL
SPN SPEECH NOISE
TD THRESHOLD OF DISCOMFORT
WN WHITE NOISE

RESPONSES

CONSISTENT ☐ INCONSISTENT ☐
RAPID ☐
SLOW ☐
DELAYED ☐



AUDIOGRAM KEY

RIGHT LEFT
AC UNMASKED ☐ ☐
AC MASKED ☐ ☐
BC MASTOID UNMASKED ☐ ☐
BC MASTOID MASKED ☐ ☐
BC FOREHEAD MASKED ☐ ☐
BC FOREHEAD UNMASKED ☐ ☐
BOTH ☐ ☐
BOUND FIELD ☐ ☐
EXAMPLE OF NO RESPONSE SYMBOLS ☐ ☐

AUDIOMETER

NO.:
MAKE: G/S
MODEL: 10

SPEECH HEARING LEVELS

		TYPE	SOURCE	NOISE	MCL	TD
RIGHT	HL	SPONDEE THRESHOLD <input type="checkbox"/>	TAPE DISC <input type="checkbox"/>	WN <input type="checkbox"/>	RIGHT	HL
MASKING IN LEFT	HL	AWAWARENESS THRESHOLD <input type="checkbox"/>	MLV <input type="checkbox"/>	SPN <input type="checkbox"/>		
LEFT	HL	OTHER <input type="checkbox"/>		OTHER <input type="checkbox"/>	LEFT	HL
MASKING IN RIGHT	HL					

SPEECH DISCRIMINATION SCORES

		TEST 1	TEST 2	TEST 3	STIMULI	SOURCE	NOISE	RESPONSE
RIGHT	%	HL	%	HL	W-22 <input type="checkbox"/>	TAPE <input type="checkbox"/>	WN <input type="checkbox"/>	TALK BACK <input type="checkbox"/>
MASKING IN LEFT	HL	LIBT	HL	LIBT	PS-50 <input type="checkbox"/>	DISC <input type="checkbox"/>	SPN <input type="checkbox"/>	WRITTEN <input type="checkbox"/>
LEFT	%	HL	%	HL	PS-50 <input type="checkbox"/>	MLV <input type="checkbox"/>	OTHER <input type="checkbox"/>	MULTI-CHOICE <input type="checkbox"/>
MASKING IN RIGHT	HL	LIBT	HL	LIBT	OTHER <input type="checkbox"/>			

COMMENTS:

RT EAR STIM LT EAR STIM
REFLEXES: 5K = 85 85
1K = 80 90
2F = 85 85
4K = 80 90

Jentis Audiologist

Figure 7-9

Audiometric test results for Mike Ohmart. Acoustic reflex thresholds are listed at the bottom of the page.

driving the underwater projector; and (3) the use of sound pressure levels, both for the in-air and underwater signals, that at times were high enough to activate the acoustic reflex, and the use of a perhaps less-than-optimum on-off time sequence for this situation.

Although background noise spectra were not measured during the equal loudness tests (it was not initially expected that this would be necessary), some judgments concerning the in-air noise problem can be made based upon the data obtained with the sound level meters. Recall that SPLs were measured in both the A-weighting mode and in the no-weighting mode. If there were no significant background noise interference, then the meter readings at any one of the test frequencies should have differed only by the A-weighting value at that frequency. The meter would be measuring the level of the tone signal alone. Table 7-4 lists the A-weighting values in dB. We see that at the frequencies used in the equal loudness experiment--i.e., 1, 2, and 4 kHz--the differences in the absence of interfering noise should be 0.0, +1.2, and +1.0, respectively. If the differences do not agree with these values, then it is reasonable to assume that frequency components in addition to the pure tone are present--i.e., noise components--and that these may be interfering with the experiment in two ways: first, by masking of the in-air pure tone; and second, by causing a false measure of the SPL for the tone. (It is questionable that a valid equal loudness test can be conducted in the presence of even moderate levels of audible noise occurring *in only one of the two media*. Even if critical bandwidth masking does not occur because of low levels within the band, the broadband noise present in one medium and not in the other could very well be a *distraction* to the experiment.)

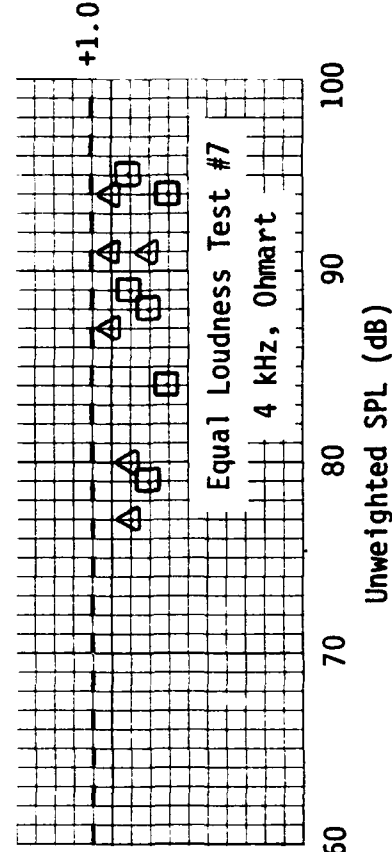
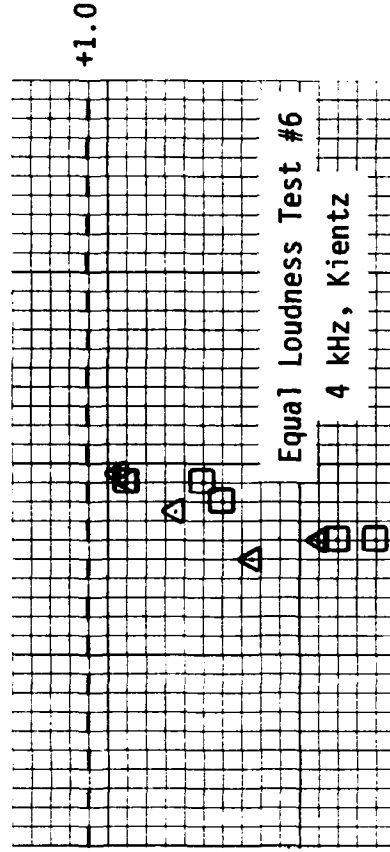
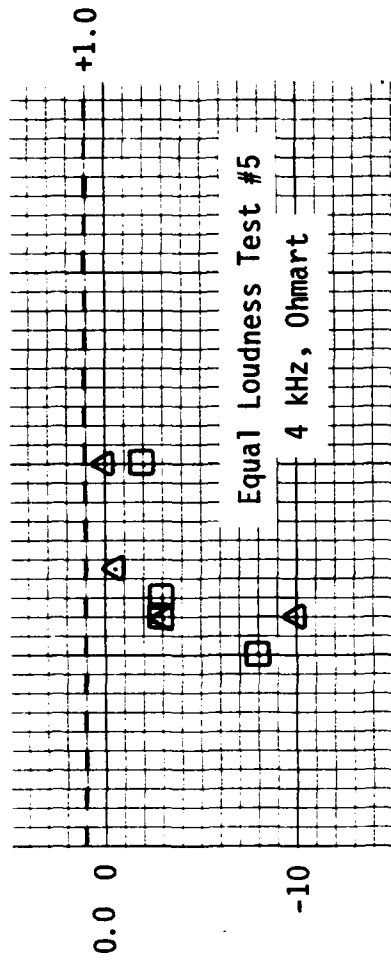
Figure 7-10 shows the *differences* (in dB) between the measured A-weighting and no-weighting in-air sound pressure levels plotted versus the unweighted SPL for the seven equal loudness tests listed in Table 7-2. The dashed horizontal line in each graph represents the expected difference if there were no significant background noise present. It is apparent that many of the data groups in these graphs fall below the *no-noise* expected values, and some by fairly large amounts suggesting the presence of strong components of lower frequency noise.

Because of the lack of control of the pool acoustic environment during the relatively brief test periods, the in-air background noise conditions were frequently changing. Pumps were turned on and off producing varying machinery noise, and resulting inflow and outflow noise, which sometimes came in surges, contributed to the general background. The excess water overflowed into a channel running completely around the top of the pool, and when the rate of water flow was high, a high level of overflow splashing

Table 7-4. A-weighting values as a function of frequency
(from Harris, 1979, page 2-9).

<u>Frequency (Hz)</u>	<u>A-weighting (dB)</u>
50	-30.2
63	-26.2
80	-22.5
100	-19.1
125	-16.1
160	-13.4
200	-10.9
250	-8.6
315	-6.6
400	-4.8
500	-3.2
630	-1.9
800	-0.8
1,000	0.0
1,250	+0.6
1,600	+1.0
2,000	+1.2
2,500	+1.3
3,150	+1.2
4,000	+1.0
5,000	+0.5
6,300	-0.1
8,000	-1.1
10,000	-2.5

△ Sound Meter No. 2



□ Sound Meter No. 1

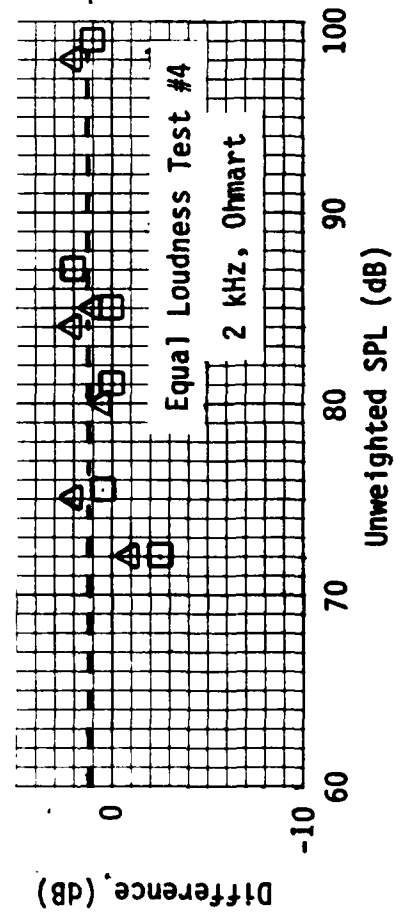
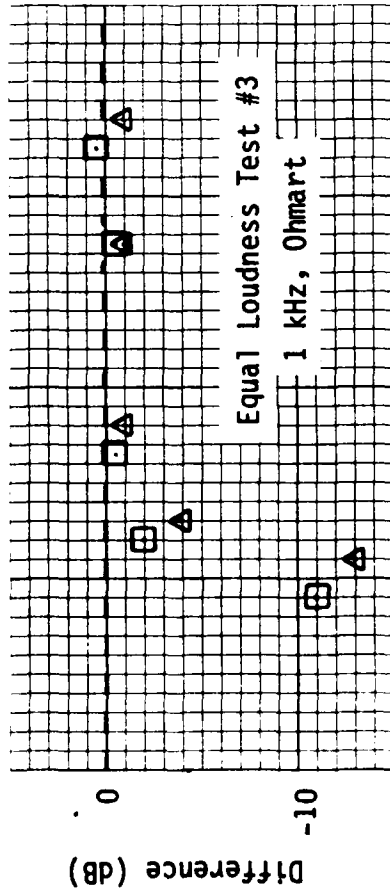
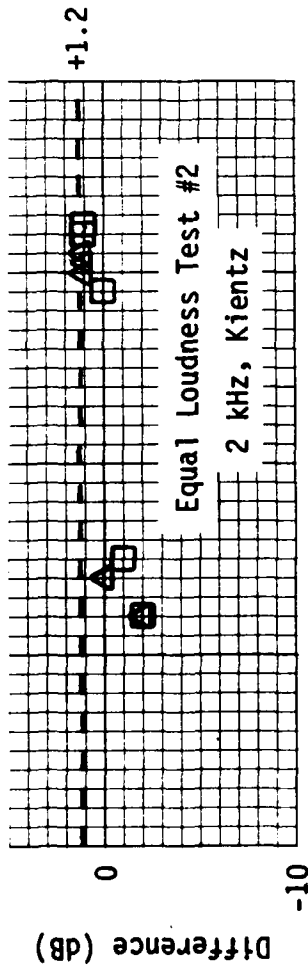
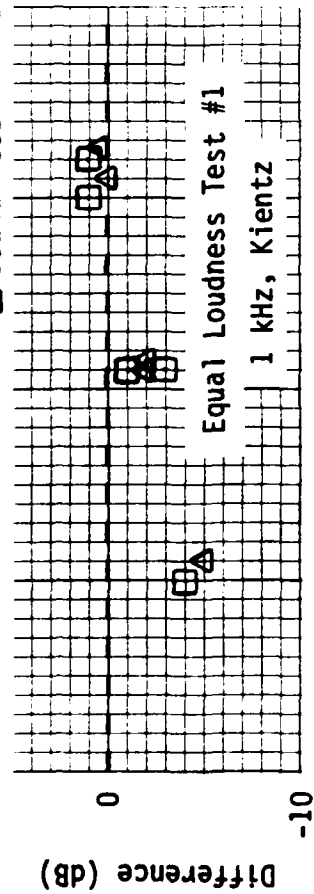


Figure 7-10

Differences between measured in-air A-weighted SPLs and unweighted SPLs (A-weighted minus unweighted) obtained during the seven equal loudness tests. The dashed horizontal lines represent the expected differences if there were no background noise.

noise was heard. At times, the tests had to be stopped because the *overall* noise was obviously excessive.

In retrospect, experimental personnel generally agreed that the in-air background noise probably was never less than in the range of 65 to 70 dB (unweighted). It is quite likely that the lowest SPL values for which data are plotted in Figures 7-11a through 7-11g, which show the underwater versus in-air SPL differences for the seven equal loudness tests, are fairly indicative of the background noise levels existing at the start of each test. For example, specific observation notes recorded during tests E.L. 5 and E.L. 6 show that this was approximately the case for these two tests (approximately 70 dB and 76 dB respectively were the noted background noise values). The scatter in the plotted data shown for E.L. 6 in Figure 7-11f also suggests that it was a particularly noisy test (i.e., 76 dB of unweighted background noise). In contrast to the high levels of in-air noise, underwater noise did not seem to be a problem. The underwater tone signal levels were always well above any background noise in the water.

The result of the in-air noise problem was to make the unweighted in-air SPL values fictitiously high and thus the differences between the underwater and in-air SPLs unrealistically low, particularly for the lower sound levels. This can be observed in most of the plots of Figures 7-11a through 7-11g as a general upward trend in the difference values with increasing sound level (ignoring the two anomalous low data groups for E.L. 1 at 81 dB and for E.L. 2 at 89.5 dB). It is likely that only the larger difference values occurring at the higher SPLs are representative of the true differences between underwater and in-air hearing.

The data for E.L. 3 (Figure 7-11c) do not exhibit the upward trend at the higher SPL values (i.e., at 88 and 93 dB) as observed in many of the other tests. It is possible that an activated acoustic reflex was causing some attenuation of the in-air sound at the higher levels. This would result in smaller SPL differences between the underwater and in-air conditions. Attenuation would *not* occur for the underwater bone-conducted sound since the middle ear is effectively bypassed. The audiometric examination of Mike Ohmart, who was the subject in test E.L. 3, showed a contralateral acoustic reflex threshold at 1000 Hz of 80 dB (hearing level) for the right-ear-stimulus situation, and 90 dB for the left-ear-stimulus case. (The accuracy of these values is probably in the range of ± 5 -10 dB and therefore the difference of 10 dB between the left and right ears should not be taken as absolute.) For these tests, the right ear was under water and was stimulated by the underwater tones. The left ear, however, was stimulated by both the in-air tone as well as any high levels of background noise. As discussed in Section 8 of this report,

In-water sound pressure measured with hydrophone:

- △ Behind the head,
- Under the ear,
- + In front of the face.

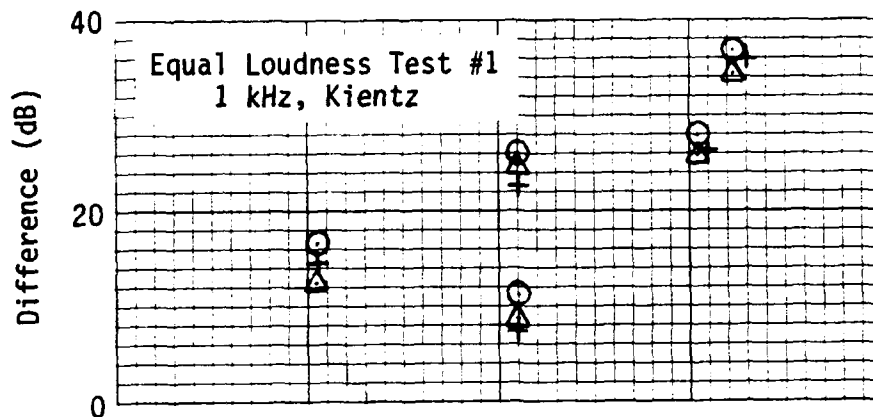


Figure 7-11a

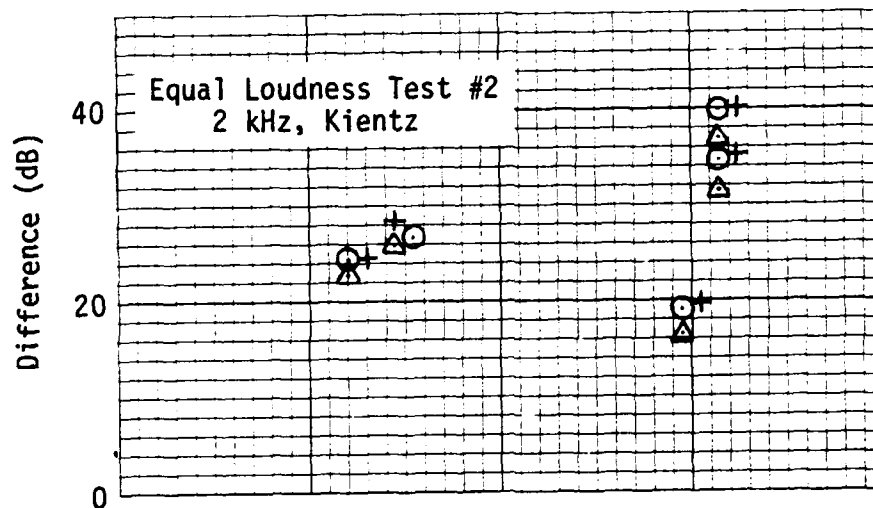


Figure 7-11b

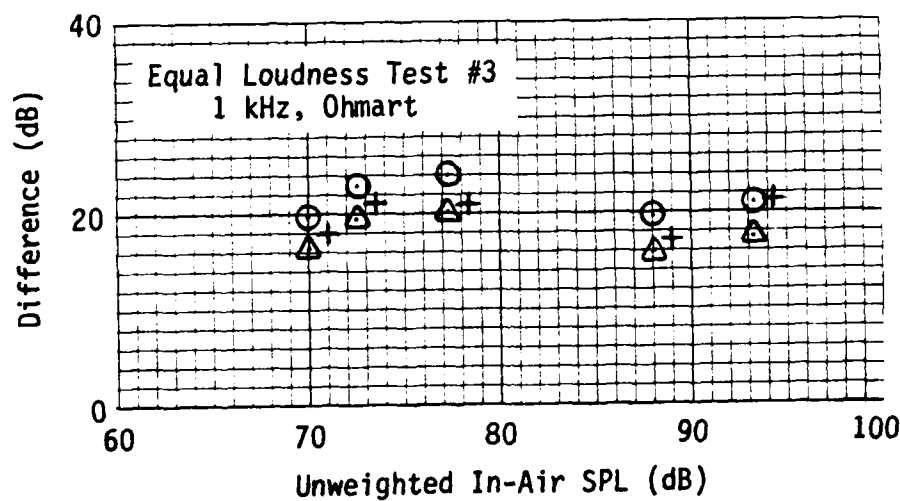


Figure 7-11c

Figure 7-11

Differences between underwater and in-air sound pressure levels (underwater minus in-air) based upon equal loudness judgments by two subjects, plotted versus the measured no-weight in-air SPL. The uphill trend observed in many of the graphs indicate contamination by in-air background noise at the lower sound levels.

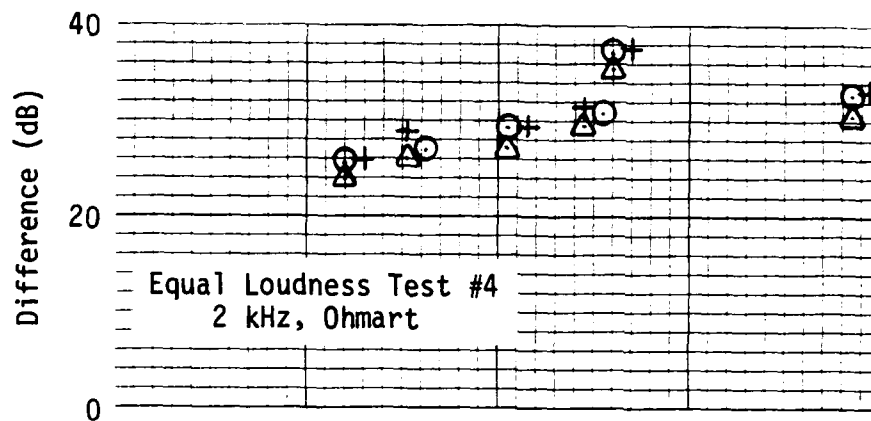


Figure 7-11d

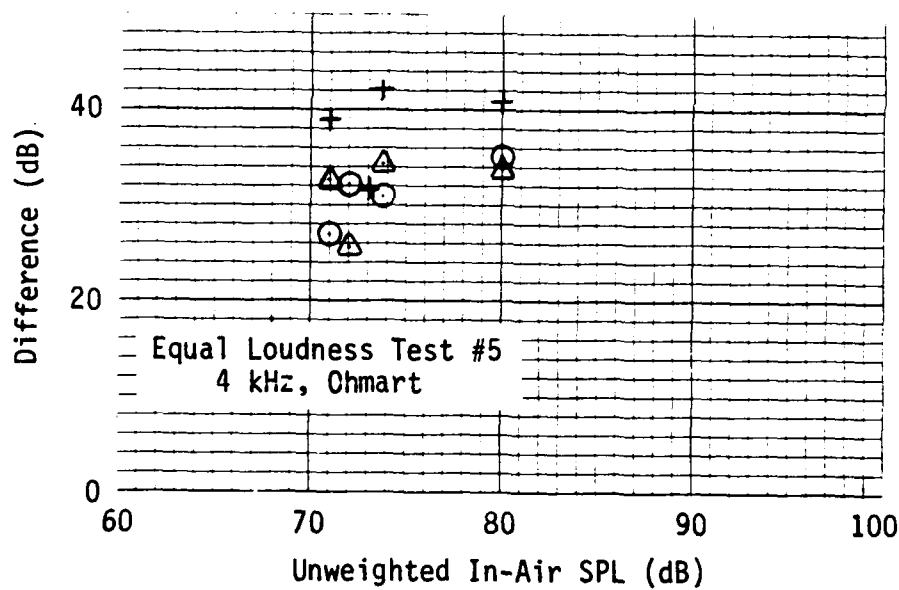


Figure 7-11e

Figure 7-11 (Continued)

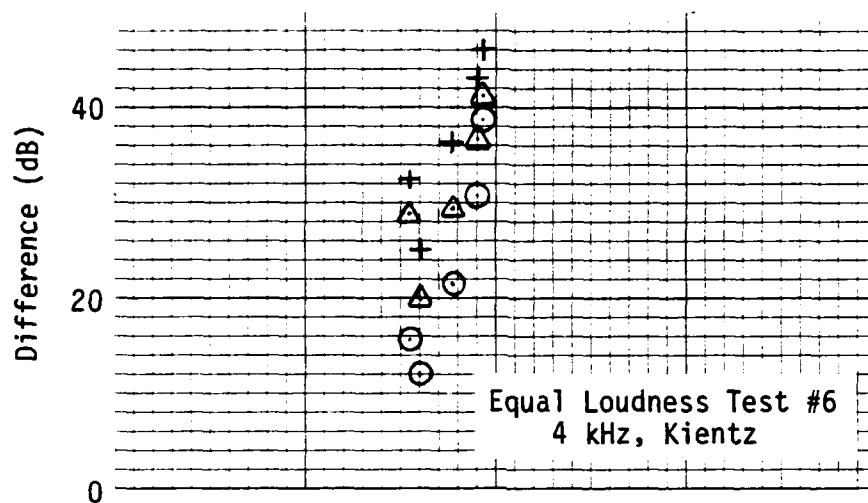


Figure 7-11f

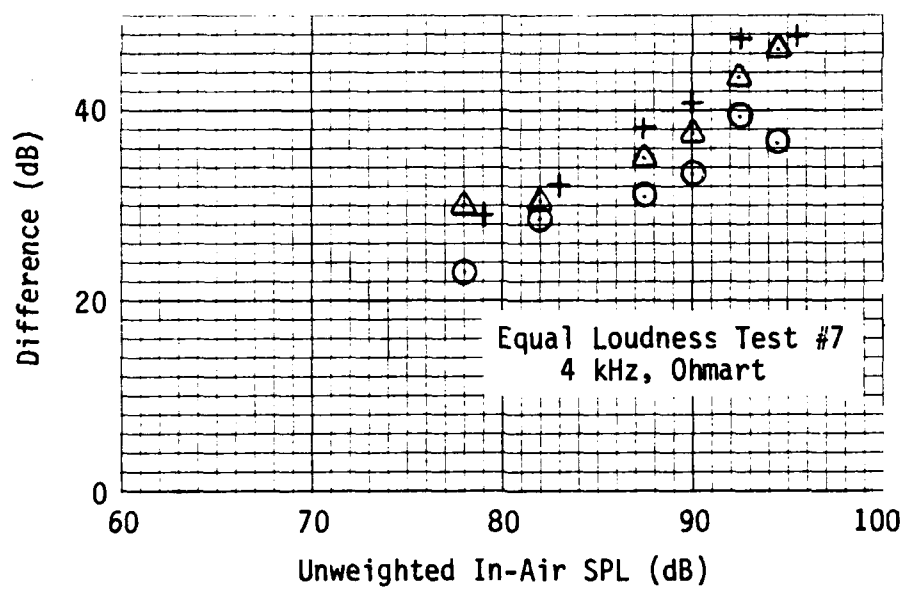


Figure 7-11g

Figure 7-11 (Continued)

about an 87-91 dB SPL for monaural 1000 Hz tones in air will elicit a reflex contraction of the middle ear muscles (reflex threshold). The reflex thresholds for white noise, however, are significantly lower being in the 70-80 dB SPL range. Thus the *varying* levels of in-air background noise combined with the in-air signals (tones) could have elicited the acoustic reflex at various times during the experiment. Further, the underwater signals reached levels that also could elicit the acoustic reflex (our acoustic reflex tests, to be discussed next, indicate an ART of 125-130 dB underwater SPL at 1 and 2 kHz).

Since the acoustic reflex attenuates sound transmission only for frequencies below about 1500 Hz (again see Section 8), one would expect to see reflex effects only in the 1000 Hz tests of this experiment; i.e., in tests E.L. #1 and #3. It is possible that some of the low data groups in these two tests were caused at least in part by acoustic reflex effects. However, the low data group at 89.5 dB SPL in E.L. #2 could not be explained in this way since the test was conducted at a frequency of 2 kHz. Further, the attenuation produced by the acoustic reflex (in air) would probably not be as large as suggested by the low data groups in the 1 kHz tests.

It is more likely that the low data groups and apparent inconsistencies in the equal loudness test results were caused by changes in the background noise level that took place unexpectedly during the various test periods. Sudden increases in in-air noise level as well as changes in spectral content could create greater masking, requiring the in-air tone level to be increased to obtain *equal loudness* with the underwater tone. In order to avoid these problems in future tests, a controlled quieter environment will be necessary. The in-air signal levels employed probably should be 30 dB or greater above the critical band noise levels. Therefore, the background noise must be kept to a minimum; certainly well below the 70-80 dB SPL encountered in this series of tests.

As discussed in Section 8 of this report, the amount of attenuation provided by the acoustic reflex has not yet been clearly established in the available research literature. It is interesting to consider that the proposed equal loudness test concept for comparing underwater and in-air hearing could provide this type of information. One would expect the equal loudness differences between the underwater and in-air SPLs to be constant as the signal levels are increased up to the point at which the acoustic reflex is activated. From then on, the differences (at the lower frequencies) should decrease because the reflex would not provide attenuation for the underwater bone-conducted sound. The level of the underwater sound would have to be *turned down*, in a relative sense, to match the attenuated in-air signal. The differences should grow smaller the greater the signal

levels (above ART) until the maximum attenuation is reached. The dependence on frequency could easily be established.

In order to estimate the *allowable* in-air background noise level for conducting a better-controlled equal loudness test, let us assume a flat noise spectrum over the audio frequency range; the spectrum level then would be slightly greater than 40 dB below the overall noise level (40.8 dB for a sound meter bandwidth of 0-12,000 Hz and 43 dB for a bandwidth of 0-20,000 Hz). The critical bandwidth level would be about 20 dB above the spectrum level (18 dB at 1 kHz, 20 dB at 2 kHz, 23 dB at 4 kHz, etc.--see Beranek, 1986, Figure 12.2). Therefore the critical bandwidth level in the mid-frequency range would be about 20 dB (~ 40 minus ~ 20) below the overall SPL as measured by a sound level meter (unweighted). Now, if the difference between in-air and underwater hearing is nominally 50 dB (the actual difference may be less than this value and may vary somewhat with frequency as indicated elsewhere in this report), and an underwater SPL of say 100 dB is being generated at a subject's head position, then the equivalent (equal loudness) in-air SPL in the absence of noise for this situation would be 100 minus 50, or 50 dB (well below the point at which the acoustic reflex would be activated). In order to meet the 30 dB requirement (signal 30 dB above critical band noise level), the critical band noise level should be no greater than 50 minus 30, or 20 dB. This would allow the overall unweighted background noise level to be about 40 dB (20 plus 20), which is the kind of noise level encountered in a rural home under quiet conditions.

It may be difficult to achieve this degree of in-air quiet above any body of water that we might practically select for this experiment. However, we can probably allow an additional 10 to 15 dB of background noise and still obtain valid results. A background noise level of 50-55 dB can be obtained with careful site selection and control of local noise sources. In any future experiment, the background noise *spectrum* should be measured so that the *actual* masking effects can be determined. Our assumption of a *flat* noise spectrum for estimating the amount of allowable noise may not be valid for any particular site. It is not uncommon for background noise to be dominated by lower frequency sounds with the SPLs falling off at the higher audio frequencies. Our estimate based upon a *flat* spectrum, therefore, may be overly conservative at some frequencies and underly conservative at others.

In summary, the equal loudness tests demonstrated that, by selecting a site having low levels of in-air background noise, useful comparative data between underwater and in-air hearing can be obtained. Further, this experimental approach can provide information (which is presently sparse or lacking) on the *attenuation* provided by the acoustic reflex in air. Better control and monitoring of in-air background noise will be required and this should include *adequate spectrum measurements* so that masking levels can be determined. The on-off pulse sequence timing should probably be changed to allow the acoustic reflex to completely stabilize *when activated* and to fully fade away upon cessation of the signal. (A timing sequence similar to the acoustic-reflex-test timing could be used but with alternate switching between the in-air speaker and underwater transducer.)

7.5.2 Acoustic Reflex Test Results

Because of time constraints, the acoustic reflex tests were conducted at only two frequencies; viz., at 1 kHz (Kientz and Ohmart) and at 2 kHz (Kientz). Only the right ear for each subject was positioned underwater and was stimulated by the tones from the underwater transducer. There was insufficient time to test the opposite ear. The acoustic reflex probe was inserted in the contralateral ear which was just above the surface of the water.

An otoadmittance meter was used to detect the activation of the acoustic reflex and to measure the relative impedance changes as the underwater sound levels were varied. The susceptance output (B) of the instrument was fed to a strip chart recorder. Changes in the susceptance values (ΔB) as the underwater tones were cycled on and off were also observed on the meter face of the instrument and recorded manually. The on-off times were sufficient to allow the reflex to activate fully and then to fade away completely. A sample segment of the strip chart is shown in Figure 7-12.

For each of these tests, a high underwater sound pressure level (e.g., 145-150 dB) was used initially to obtain a strong reflex action which could be observed easily. The sound levels were then decreased in steps as each test progressed until a change in susceptance could no longer be detected. The underwater levels were measured with equipment identical to that used in the equal loudness tests; i.e., using the same reference hydrophone, etc. However, at this point in the experiment (last day) the events were being very rushed and, in order to obtain *some* data at more than one frequency and with more than one subject, the probing of the underwater sound field was less than optimal. Only a single SPL value was obtained for each sound level by manually raising and lowering the reference hydrophone along one of the underwater transducer support ropes

Kientz, 1 kHz, Start of Acoustic
Reflex Tests, SPL Not Yet Recorded

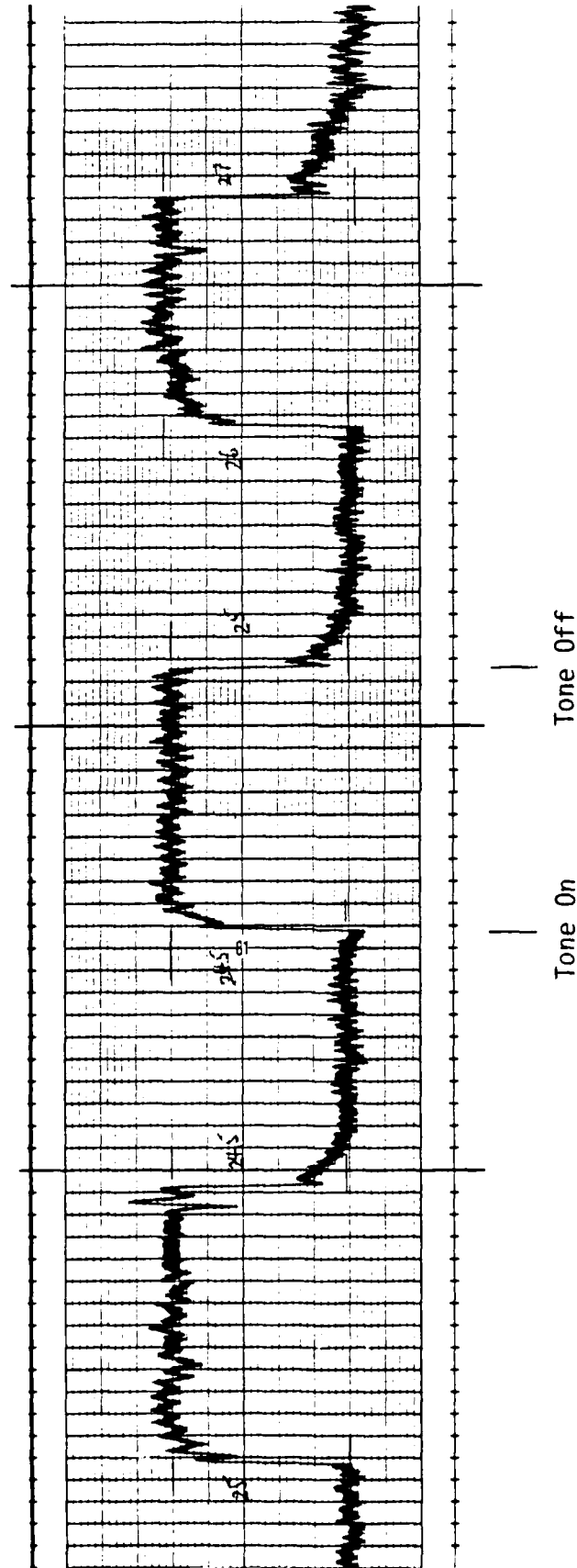


Figure 7-12

Sample strip chart record showing change in susceptance as the acoustic reflex is activated by pulsed tones.

at a position about 2 ft away (horizontally) from the diver's head position. The peak value obtained nearest the surface was recorded as the SPL. (This technique had just been used for the last equal loudness test with Mike Ohmart using a frequency of 4 kHz. The measurement along the support rope was in addition to the three measurements around the head position. The results showed that the *rope* values were either within or very near the range of values obtained for the three positions around the head. In retrospect, this probably was a poor choice of technique for the acoustic reflex tests because of the frequency differences between the last Ohmart equal loudness test at 4 kHz and the reflex tests at 1 and 2 kHz, and the associated differences in standing wave patterns. Given more time, the method of probing around the diver's head position would be preferred. The use of a single peak sound pressure value may have slightly overestimated the actual SPL, with the uncertainty probably being greater at 1 kHz than at 2 kHz.)

The results of the acoustic reflex tests are shown in Figure 7-13 and 7-14. Data were obtained for Kientz at 1 and 2 kHz and for Ohmart at 1 kHz. Only 2 data points were obtained for Ohmart before the available pool time ran out. Figure 7-13 shows the change in susceptance (ΔB in millimhos) as read off of the face of the otoadmittance meter plotted versus the underwater sound pressure level. These ΔB values were estimated averages obtained by visual observation of the meter during the pulsing sequence. Figure 7-14 is similar except that the vertical scale represents the susceptance changes as read off of the strip chart in units of strip chart divisions (there were approximately 10 strip chart divisions per unit of ΔB). These ΔB values were averages calculated from several (between 3 and 14--typically 10) measurements of the on-off pulse differences. The fitted lines in these figures intercept the horizontal axes at the following values of SPL:

Frequency	Acoustic Reflex Threshold (ART)	From
1 kHz	128.4 dB SPL	Figure 7-13
	128.3 dB SPL	Figure 7-14
2 kHz	129.5 dB SPL	Figure 7-13
	129.4 dB SPL	Figure 7-14

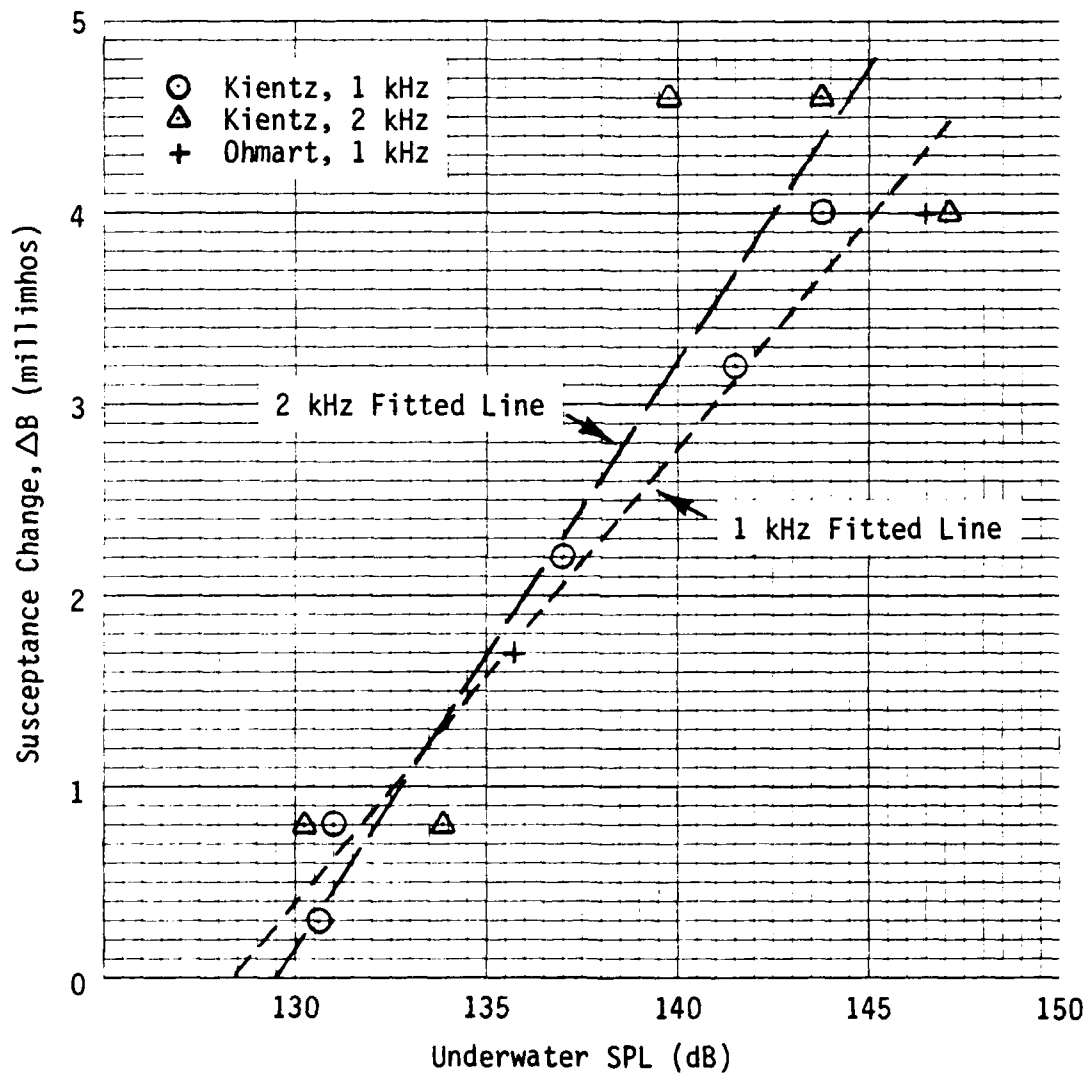


Figure 7-13

Susceptance change (from otoadmittance meter readings) versus underwater sound pressure level obtained during the acoustic reflex tests. The acoustic reflex thresholds (ART) for 1 and 2 kHz are taken as the intercepts of the fitted lines with the horizontal axis.

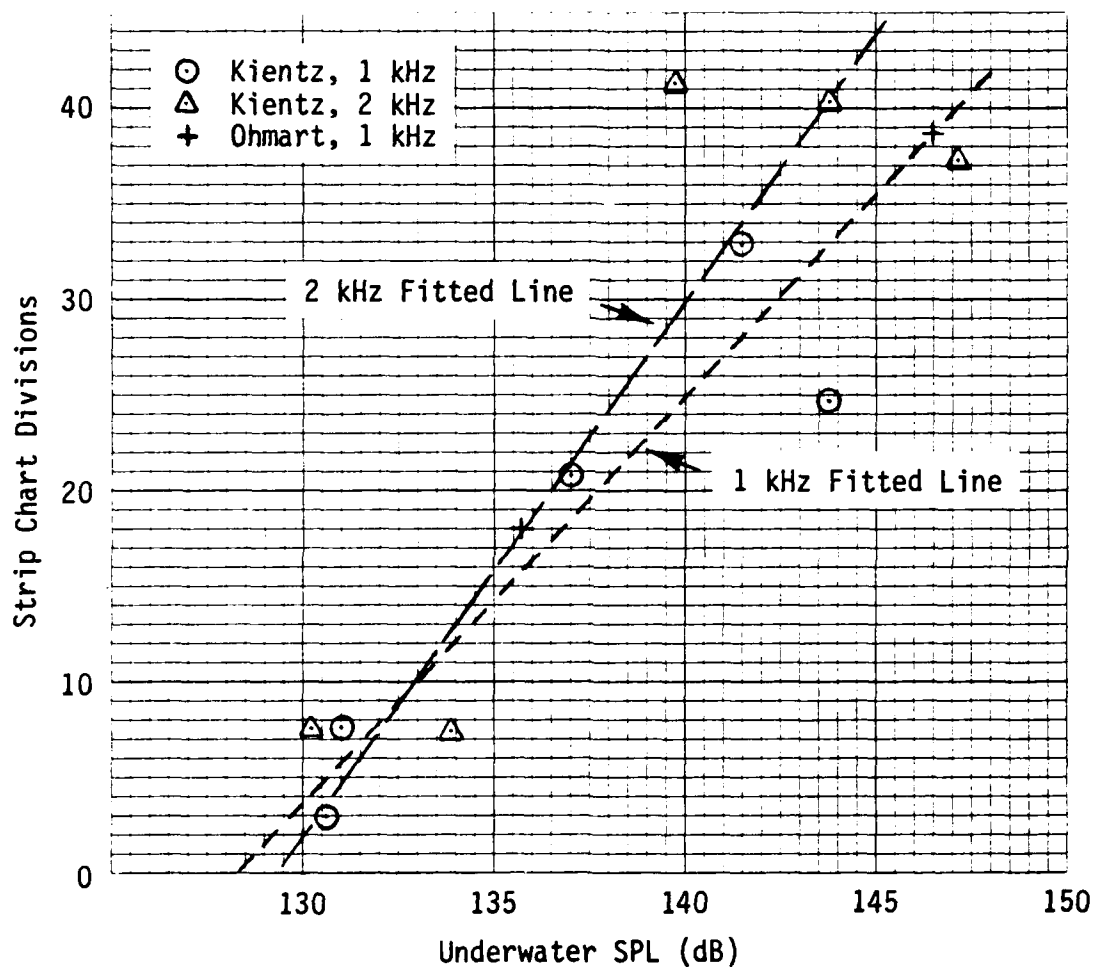


Figure 7-14

Strip chart divisions (proportional to susceptance change) versus underwater sound pressure level obtained during the acoustic reflex tests. The acoustic reflex thresholds (ART) for 1 and 2 kHz are taken as the intercepts of the fitted lines with the horizontal axis.

The exceptionally good agreement between the ARTs (intercepts) for the meter data and for the strip chart data is somewhat fortuitous in view of the amount of data scatter, particularly at 2 kHz, as well as the eyeball choice of the fitted lines. Nevertheless, the intercepts probably are correct within 1 or 2 dB of the true values.

The hearing level (HL) ARTs in air were obtained during the audiometric examinations of Kientz and Ohmart as discussed in Section 7.4. The HL ARTs for Kientz were 90 dB and 85 dB for 1 and 2 kHz respectively. The HL ARTs for Ohmart were 80 dB and 85 dB for 1 and 2 kHz respectively.* These values were for a right-ear stimulus with the acoustic reflex probe in the left ear, which corresponded to the swimming pool situation. (HL data were also available for the left-ear-stimulus situation but were not needed in this analysis.) The HL ART data were obtained using an audiometer and associated earphone (TDH-49) for the stimulus tones and an otoadmittance probe in the contralateral (opposite) ear. The ARTs were based upon the smallest change in impedance that could be reliably detected and only a single value was recorded for each frequency-subject-ear. In future tests, it would be desirable to record on a strip chart the actual changes in susceptance at different sound levels as was done in the swimming pool tests in order to provide hard copy data representing the growth of the reflex action. This would allow, perhaps, a *better* estimate of the intercept ($\Delta B=0$) value, and also would allow for measurements of the differences in the growth functions between the in-air and in-water environments. Again, at the lower frequencies, it would be expected that the reflex would grow more rapidly in water than in air as the sound level is increased because underwater hearing is via the bone conduction route. The middle ear is effectively bypassed in water and the reflex would offer no protection against the louder sounds.

The HL ARTs for Kientz and Ohmart obtained by audiometry need to be converted into equivalent sound field SPLs so that the differences between underwater and in-air hearing can be calculated. Methods for converting from audiometric data to free-field data were discussed in Section 4.7 of this report.

*As discussed elsewhere in this report, *hearing levels* (HL) are referenced to audiometric *zero* and are not directly equivalent to free-field SPLs. Refer to the following Table 7-6 for the transformation to SPLs.

Following the example of Table 4-3, individual sound pressure transformations can be made--i.e., earphone to ear canal entrance, ear canal entrance to eardrum, and eardrum to free-field. Since the TDH-49 earphone was used for the audiometric tests of Kientz and Ohmart, the appropriate MAPC values from Table 4-1 should be used in these calculations. Unfortunately, the required earphone-to-ear canal transformation values also depend upon the earphone type and these are not readily available. However, Michael and Bienvenue (1977) have shown by real-ear threshold comparisons using ten trained-listener subjects with normal audiometric thresholds that there is no significant real-ear performance difference between the TDH-49 and TDH-39. Their results are shown in Table 7-5. It is reasonable to assume, therefore, that the sound pressures at the eardrum will be practically the same for either earphone and that the MAPC values for the TDH-39 combined with the earphone-to-ear canal entrance values for the TDH-39 can be used in lieu of the comparable values for the TDH-49 to obtain the eardrum pressures. This is done in Table 7-6.

Once the eardrum sound pressure values are determined, they must be converted to equivalent free-field SPLs. In Table 4-3, this was accomplished using transformation data from Shaw (1974) for 0° azimuth (facing the sound source). In the current acoustic reflex tests, the divers placed their right ears in the water and the sound source was directly below them. It is more appropriate, therefore, when comparing underwater and in-air hearing to use Shaw's data for 90° azimuth in the in-air transformation from the eardrum to the free field. These values have been read from Shaw's Figure 11 and included in our Table 7-6. The last column in this table contains the free-field SPL ARTs calculated from the hearing level ARTs in the manner described.

The free-field in-air ARTs can now be compared with the underwater ARTs previously presented. Recall that, because of time limitations, data were obtained only at frequencies of 1 and 2 kHz. At 1 kHz, the in-water acoustic reflex data for Kientz and Ohmart (see Figures 7-13 and 7-14) were very similar and, therefore, the data have been lumped together. At 2 kHz, only data for Kientz were obtained. Table 7-7 compares the in-air and underwater ART data, with the underwater ARTs being taken from Figure 7-14. The SPL differences between the underwater and in-air ARTs fall in the range of about 35 to 45 dB with no clear difference between the 1 and 2 kHz data.

Table 7-5. Performance differences between TDH-39 type and TDH-49 type earphones as observed in the study by Michael and Bienvenue (1977). The differences are based upon real-ear threshold level comparisons.

Freq (Hz)	Response of TDH-49P re TDH-39M (dB)	Response of TDH-49P re TDH-39P (dB)
125	-0.3	-1.0
250	+0.4	+0.2
500	+0.1	±0.0
750	+0.3	-0.2
1000	-0.3	-0.7
1500	+0.4	-0.5
2000	+0.7	+0.9
3000	-0.9	-1.0
4000	-0.2	-0.8
6000	+0.1	-0.6
8000	-0.4	-1.2

P: Plastic outer shell

M: Metal outer shell

Table 7-6. Transformation of contralateral acoustic reflex thresholds obtained by audiometry to equivalent free-field acoustic reflex thresholds.

Freq (Hz)	Subjects' ART (HL) ¹	MAPC for TDH-39 ²	Earphone to Ear Canal Entrance ²	Canal Entrance To Eardrum	Eardrum to Free-field, 90° Azimuth	Equivalent Free-field ART
500	Kientz 85 Ohmart 85	11.5	2.5	0.7	-6.2	93.5 93.5
1000	Kientz 90 Ohmart 80	7.0	3.0	1.2	-8.2	93.0 83.0
2000	Kientz 85 Ohmart 85	9.0	3.5	3.8	-14.1	87.2 87.2
4000	Kientz 80 Ohmart 80	9.5	-4.5	10.2	-14.0	81.2 81.2

Note: Refer to Table 4-3 for the references used for the various transformation values.

¹Right ear, stimulus. Left ear, reflex sensing probe.

²These values are for the TDH-39 earphone and, in combination, are comparable to those for the TDH-49 used for the audiometric ART measurements of Kientz and Ohmart.

Table 7-7. Comparison of underwater and in-air contralateral acoustic reflex thresholds (ARTs) at frequencies of 1 and 2 kHz, 90° azimuth.

<u>Freq (Hz)</u>	<u>Underwater ART (dB)</u>	<u>In-Air ART (dB)</u>	<u>Difference (dB)</u>
1000	128.3	Kientz 93.0	35.3
		Ohmart 83.0	45.3
2000	129.4	Kientz 87.2	42.2

7.6 Summary and Conclusions Regarding the Equal Loudness and Acoustic Reflex Test Approaches

7.6.1 Comparison of Test Results

The acoustic reflex data of Table 7-7 show differences between underwater and in-air hearing that fall in the range of 35 to 45 dB SPL (90° azimuth situation). It is interesting to note that the equal loudness test results, even though they were probably contaminated by excessive in-air background noise at the lower sound levels, also suggest differences at the higher sound levels of the same general magnitude as those for the acoustic reflex tests. For example, if the highest two mean difference values corresponding to the highest in-air SPLs are selected from the equal loudness test data shown previously in Figure 7-11a through 7-11g, the results of Table 7-8 are obtained. The equal loudness differences in the table fall in the range of 26.7 to 43.5 dB or, excluding the single lower value of 26.7 dB, in the range of 32.0 to 43.5 dB. This is similar to the range of 35 to 45 dB of the acoustic reflex tests; however, the frequencies used were only 1 and 2 kHz in the reflex experiment. Table 7-9 compares the data from the two different experimental approaches on a frequency basis. The tabulated results of the equal loudness tests and the acoustic reflex tests are not too dissimilar at either 1 or 2 kHz; nor do they differ significantly at 1 kHz from Hamilton's (1957) data based upon his measurements of underwater thresholds of audibility (his data have been corrected to current audiometric standards and adjusted for the subjects' in-air hearing levels). However, Hamilton's difference data are greater at 2 and 4 kHz.

Obviously, the equal loudness and acoustic reflex tests need to be repeated under conditions that are properly controlled using more subjects, more frequencies, both ears, etc. However, the limited data obtained in the preliminary experiment suggest that the differences between in-air and underwater hearing may be less than those measured by investigators such as Hollien *et al.* or Smith (see Sections 5.8 and 5.9), and that Hamilton's data (Section 5.5) may be more representative of the true differences, at least at the lower frequencies (recall that Hamilton's experiment was judged to be one of the most reliable because of the use of a good acoustic environment, good experimental procedures, etc.).

Table 7-8. SPL differences between underwater and in-air hearing for the higher in-air SPL conditions.

<u>E.L. Test Number</u>	<u>Freq (Hz)</u>	<u>Subject</u>	<u>In-Air SPL (dB)</u>	<u>Mean Difference for Highest Data Group(s) (dB)</u>
E.L. 1	1000	Kientz	90.5 92.25	26.7 35.7
E.L. 2	2000	Kientz	91.5 91.5	33.7 39.0
E.L. 3	1000	Ohmart	anomalous (see previous discussion of Figures 7-11a through 7-11g)	
E.L. 4	2000	Ohmart	86.0 98.5	36.7 32.0
E.L. 5	4000	Ohmart	73.75 80.0	35.7 36.6
E.L. 6	4000	Kientz	79.0 79.25	36.9 42.1
E.L. 7	4000	Ohmart	92.5 94.5	43.5 43.5

Difference Averages at 1 kHz = 31.2 dB
 2 kHz = 35.4 dB
 4 kHz = 39.7 dB

Table 7-9. Comparison at the selected frequencies of the differences between underwater and in-air hearing as measured during the equal loudness tests and during the acoustic reflex tests. Hamilton's (1957) differences based upon underwater thresholds of audibility are also shown in the last column.

<u>Freq (Hz)</u>	<u>E.L. Test Differences (dB)</u>	<u>A.R. Test Differences (dB)</u>	<u>Hamilton (1957)</u>
1000	26.7 and 35.7	35.3 and 45.3	37.8
2000	33.7, 39.0, 36.7 and 32.0	42.2	52.5
4000	35.7, 36.6, 36.9, 42.1, 43.5 and 43.5	-----	58.9

7.6.2 Some Additional Experimental Evidence Supporting Smaller Differences Between Underwater and In-Air Hearing Than Are Commonly Accepted

7.6.2.1 Montague and Strickland (1961)

There exist some additional data that suggest that the differences between underwater and in-air hearing may be less than thought. Montague and Strickland (1961), in addition to conducting an experiment to determine underwater thresholds of audibility (discussed in Sections 5.7 and 5.10.1 of this report), also conducted an experiment reported in the same article on the ability of 23 divers to *tolerate* a high intensity underwater tone of 1500 Hz. Although the *audibility threshold* measurements were considered to be questionable on the basis of the arguments given in Section 5.10.1 of this report, the high intensity tone experiment did not suffer from the same deficiencies.

The tests were performed in San Diego harbor at a depth of 25 ft. Each diver stood on the bottom with his head in a headrest. The 1500 Hz tones were emitted from a large barium titanate transducer driven by a 10-kw amplifier which produced a maximum sound pressure level at the diver's position of about 180 dB re 20 μ Pa. A reference hydrophone was used to measure the SPL at the subject's head position. An ascending series of 1 sec pulses 2 sec apart was used, with each pulse being 1 dB higher than the preceding one. Each diver was asked to signal when the sound level became "too unpleasant....to permit further increase." Measurements were made with the subject facing the transducer with and without a diving hood. Measurements were also made with the subject facing right and facing left with the hood off. With the hood on, almost all of the subjects could stand all SPLs up to the maximum. The results for the *hood-off* measurements are shown in Figure 7-15 in which the percent of divers tolerating the signal is plotted against the signal level. At the 50 percent point, the SPLs fall between 172 and 176 dB. The figure also shows that fewer subjects can tolerate a given signal level when facing the transducer than when turned 90° right or left. The data at the 50 percent level suggest that the tones sound louder by 2 to 3 dB for the face-on condition than for the 90° conditions.

Montague and Strickland in their concluding remarks state:

"The tolerance limits underwater represent a shift, from similar data in air, of about 40-50 db. Although this corresponds reasonably well with Hamilton's observation of the amount of sensitivity to weak signals lost by the

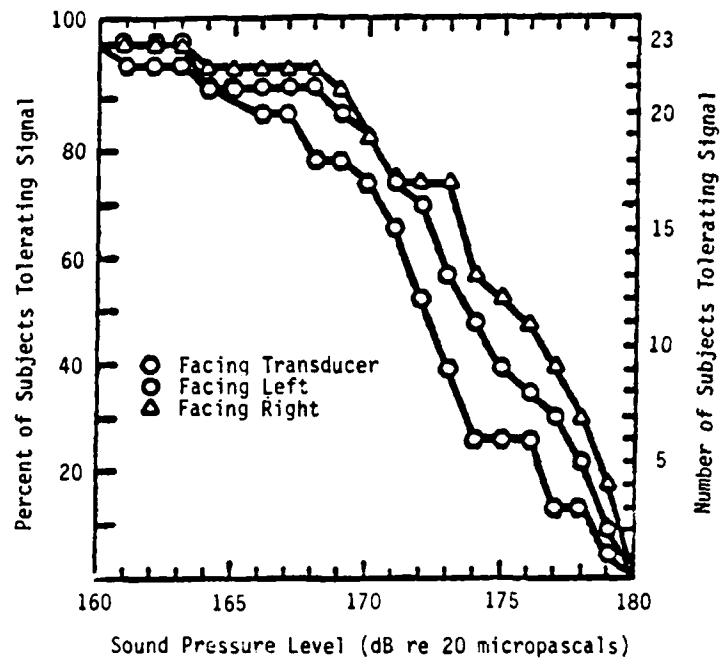


Figure 7-15

Number of hoodless divers tolerating high-level underwater tones at 1500 Hz (after Montague and Strickland, 1961).

water-immersed ears, it is considerably less than the loss found by Wainwright, and that found in our experiment. There seems to be no obvious reason for this discrepancy."

It may be that the difference of 40-50 dB between these *suprathreshold* tolerance limit data and similar data in air is more truly representative of the actual difference (at this frequency) between underwater and in-air hearing than indicated by many of the *threshold* experiments. Hamilton's work has been judged earlier to be one of the better threshold experiments. The agreement of these suprathreshold data with his data tends to support his lower thresholds of audibility for the underwater environment.

Montague and Strickland asked 4 of their subjects to judge when they felt the sound. This effect seemed to occur "about 10 dB below the tolerance level when no hood was worn." This would place the sound level at 162-166 dB for the 50 percent value in Figure 7-15. In air, a representative threshold of feeling for a population is about 120 dB (Harris, 1979, page 8-5; Denes and Pinson, 1963, page 77). As before, these data suggest a difference between underwater and in-air hearing that falls in the 40-50 dB range. Visual effects such as apparent rotational motion of the field of view referred to as *oculo-gyral motion* also were encountered by *all* of the divers and were first noticed at an SPL of about 165 dB (although no quantitative data were obtained, the *maximum* SPL used in the experiment was 180 dB). In air, vestibular system stimulation effects such as dizziness and nystagmus (rapid back and forth movements of the eye) occur at SPLs on the order of 130-140 dB (Kryter, 1985, pages 451-452). Again, these data suggest underwater-versus-in-air differences in the range of 40-50 dB (or less) at the frequency of 1500 Hz.

Although the signal levels used in Montague and Strickland's tolerance limit experiment were all high enough to activate the acoustic reflex, there would be little if any attenuation provided by the reflex. In water, the middle ear is bypassed by the bone-conducted sound. For equivalent (in the sense of producing the same effects) levels in air, the acoustic reflex does not appear to provide much attenuation at a frequency of 1500 Hz (see Section 8.3 of this report). Therefore, the difference estimate (underwater versus in-air) of 40-50 dB would be expected to be valid for SPLs below the reflex activation level, as well as above. At frequencies below 1500 Hz, the differences between underwater and in-air hearing could be perturbed by activation of the acoustic reflex and its attenuation of airborne sound.

7.6.2.2 Smith and Wojtowicz (1985)

Another experiment that strongly suggests that the differences between underwater and in-air hearing sensitivity are significantly less than previously thought was performed by Smith and Wojtowicz (1985) of the Naval Submarine Medical Research Laboratory. The intent of the experiment was to find sound pressure levels in air and in water that would produce equivalent amounts of temporary threshold shift, or TTS (see Section 7.1 for a description of TTS). It was planned eventually to test three groups of eight divers each, using a "three-factor mixed design" approach in which frequency, sound pressure level, and the medium (air or water) would be varied. However, only four divers were tested before the experiment was aborted due to the development of excessive TTS in the underwater sound exposure environment among all four subjects. It would appear that, in the experiment's design, the underwater sound pressure levels were selected based upon previous experimental work in which the differences between underwater and in-air hearing sensitivity were determined from measurements of thresholds of audibility (see Section 5 of this report--in particular Section 5.9 dealing with Smith's earlier experiments). The *assumed* differences for this TTS experiment seemed to be in the neighborhood of 60-70 dB, but with the exact amount depending upon frequency. For example, in the case of the subject designated "Diver A", the in-air exposure was at 100 dB SPL and the underwater exposure was at 165 dB SPL; a difference of 65 dB.

Table 7-10 lists the tone frequencies, SPLs, and TTS_2 values for the in-air and underwater exposures of each of the four divers. Each TTS audiometric test frequency was about 1/2 octave above the exposure frequency. The 25-minute in-air exposure test was conducted for each subject on one day and the 25-minute underwater exposure test was conducted the following day. TTS values were determined by audiometric measurements before and immediately after the exposures. Threshold measurements were continued for a 48-hour period after the underwater exposure in order to track the recovery for each subject.

The in-air exposure tones were delivered through a TDH-39 earphone driven by appropriate electronic equipment. The underwater exposure tones were delivered by one of two transducers positioned 36-in. apart at a depth of 20 ft (in a 20 ft x 60 ft x 35-ft deep pool). The subjects using open-circuit SCUBA were "four young Navy divers who had normal hearing levels." Each diver's head was positioned halfway between the two transducers. The subject faced perpendicular to a line between the transducers so that the sound was arriving either from the right or left sides. The 700 Hz and 1400 Hz tones came from the transducer (Honeywell HX-188) to the left and the 5600 Hz tone came

Table 7-10. Temporary threshold shifts (TTS_2) produced by 25-minute exposures to tones in air and in water at specified frequencies and sound pressure levels. Data from Smith and Wojtowicz (1985). (TTS_2 is the temporary threshold shift measured 2 minutes after cessation of exposure.)

Subject	Test Ear	Freq (Hz)	In-Air SPL (dB)	In-Air TTS_2 (dB)	In-Water SPL (dB)	In-Water TTS_2 (dB)
Diver A	Right	5600	100	5 to 6 @ 8000 Hz	165 Nominal (165.1 Average, Range 157.6 to 170.8)	36 @ 8000 Hz
Diver B	Right	1400	95	5 @ 2000 Hz	153 Nominal (143.7 Average, Range 129.7 to 151)	23 @ 2000 Hz
Diver C	Left	700	95	27.5 @ 1000 Hz (Interpolated: $TTS_1 = 24$, $TTS_3 = 31$)	160 Nominal (160.9 Average, Range 152.8 to 167.8)	47 @ 1000 Hz
Diver D	Left	1400	90	6 @ 2000 Hz	163 Nominal (161.3 Average, Range 156.3 to 166.1)	39 @ 2000 Hz

from the transducer (USRD F56) to the right. A USRD F50 hydrophone was used for SPL measurements which were made at the position of the center of the diver's head when the diver was not present (it was reported that "the presence of the diver and his exhaust bubbles distorted the sound field").

Because unexpectedly large TTS values resulted from the underwater exposures, further sound field mapping was done using two additional divers to determine the effect of their presence, including their exhaust bubbles, on the sound field. These mapping data were used to estimate the *actual* exposure SPLs for the four subjects which are included in parentheses in Table 7-10.

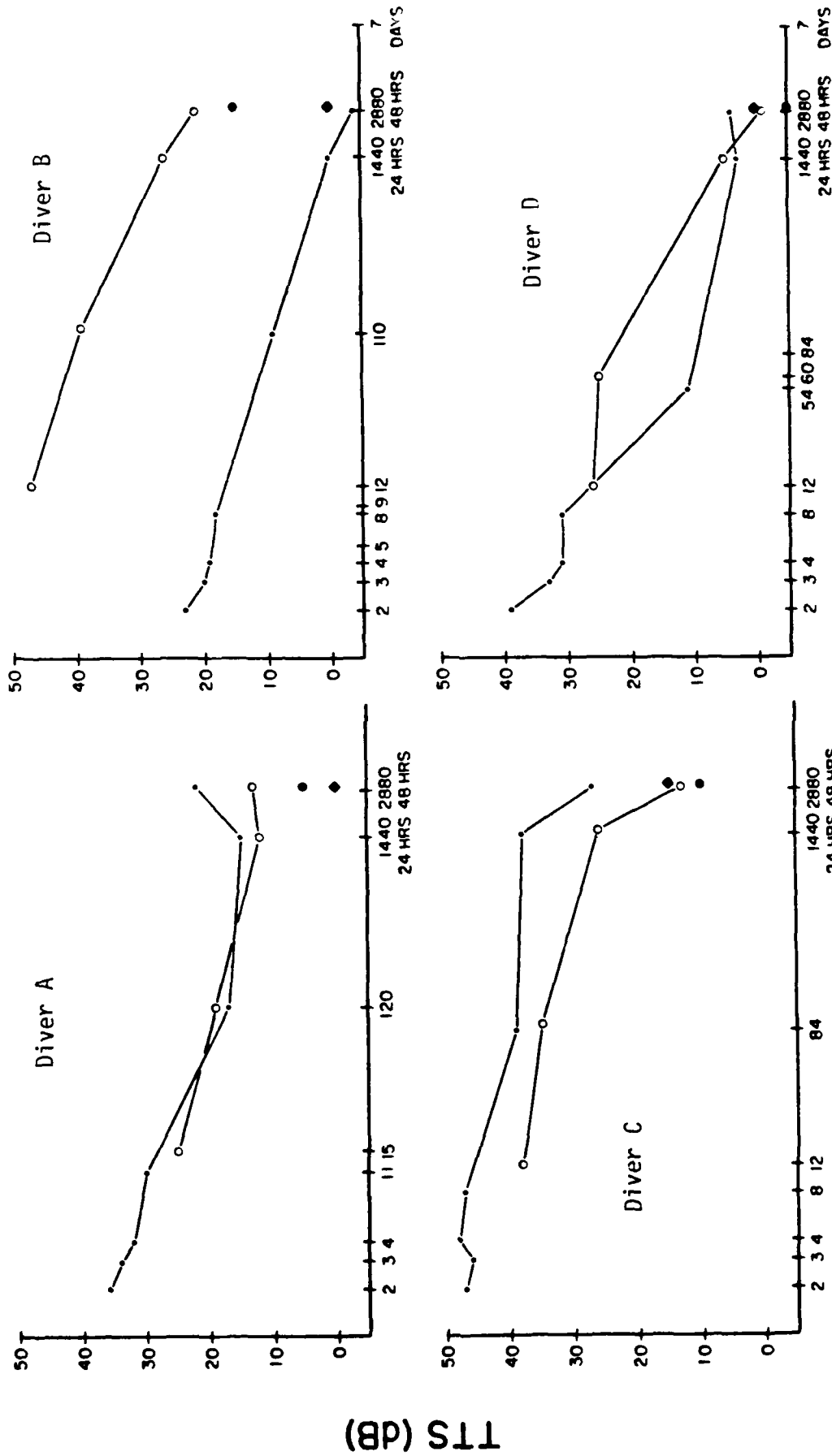
Figure 7-16 shows the TTSs resulting from the underwater exposure and its recovery for each of the four subjects used in the experiment, as presented by Smith and Wojtowicz. (Note: For Diver B, his test ear was reported to be farther from the active transducer than his contralateral ear and was subjected therefore to a lower SPL; i.e., test ear 143.7 dB average, contralateral ear 151.3 dB average). Similar to the experience of Montague and Strickland in their tolerance limit experiment (see Section 7.6.2.1), Smith and Wojtowicz indicated that the "subjects reported nonauditory effects usually associated with exposure to sound in air at 120 to 140 dB." These effects included feelings of head vibration, tickling sensations in the ear, ringing in the ear (tinnitus) following exposure, and for one diver a feeling of *watering eyes* during the exposure. The same subject (Diver D) experienced a "bloody left ear (Teed class 2-3) a few hours after the exposure and pain in both ears.... for at least two days following the exposure."

In their concluding remarks, Smith and Wojtowicz state that:

"These data do not point to a noise level at which divers may safely be exposed, but they do indicate that exposures to similar conditions ought to be avoided."

In spite of this somewhat conservative position taken by these investigators, fairly good estimates of the differences between underwater and in-air hearing *can* be derived from their data for each of the four divers and these, in combination with other experimental evidence, can *point toward* the establishment of *better* noise exposure limits for the underwater environment. Obviously, the relatively small TTS values resulting from the in-air exposures of the four divers and the very large TTS values resulting from the underwater exposures *strongly* suggest that the assumed differences between hearing sensitivities in these two media are grossly in error. To obtain estimates of what these

●—● TEST EAR ◆ CLINIC
 ○—○ CONTRALATERAL EAR ● CLINIC



TIME (MIN)

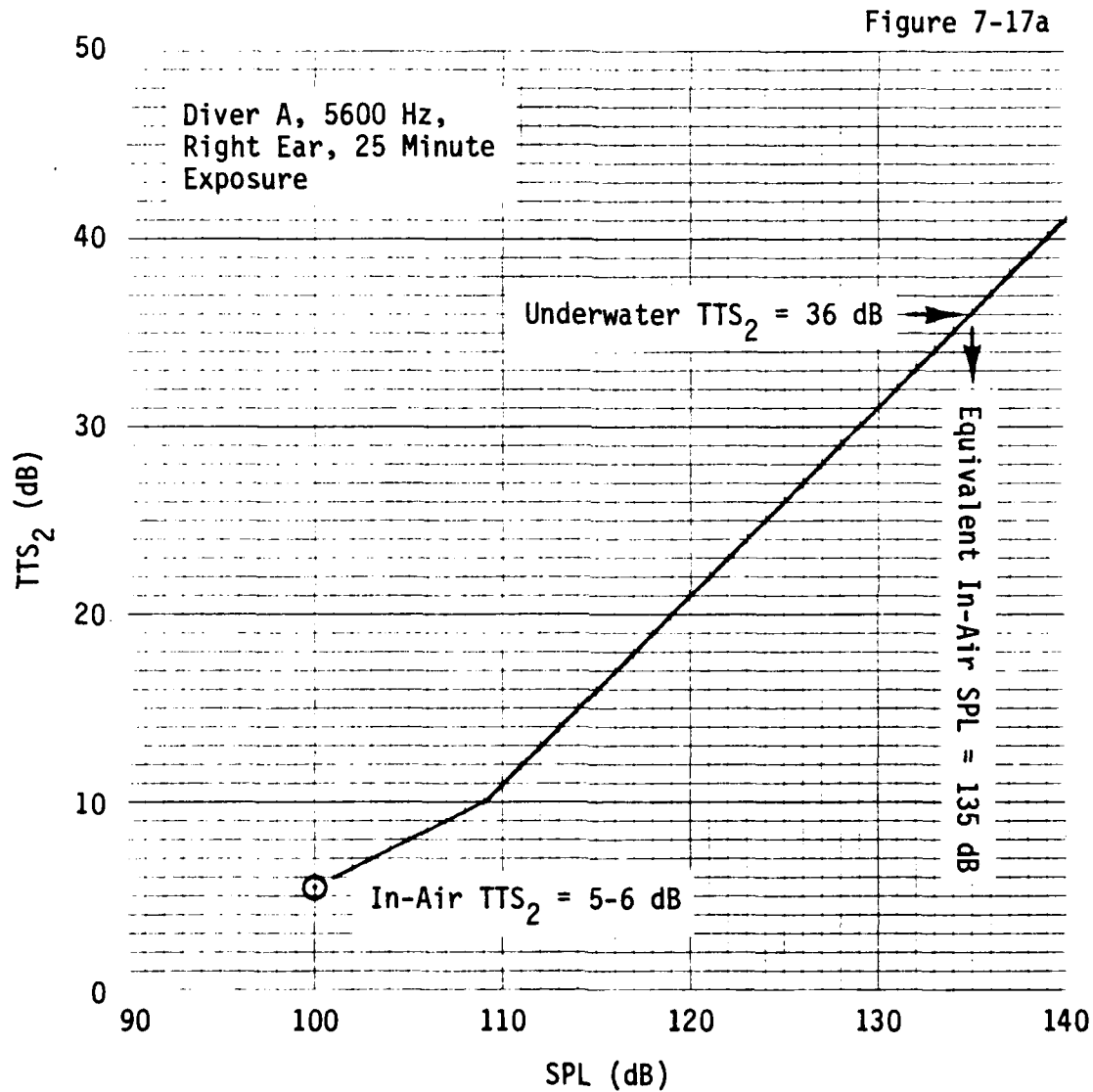
Figure 7-16

Temporary auditory-threshold shifts for four divers (A, B, C, D) as a function of time following cessation of the exposure. Time is plotted on a logarithmic scale. (From Smith and Wojtowicz, 1985.)

differences would be for these four divers based upon equivalent TTS, an extrapolation of the in-air TTS values to higher SPLs can be made using the relationship between SPL and the growth of TTS provided by Kryter (1985), pages 246-254. Based upon a large number of TTS studies, he indicates that TTS will grow about 0.5 dB for every 1 dB increase of SPL up to a TTS value of 10 dB. Above 10 dB, TTS will grow about 1 dB for every 1 dB of SPL increase. Figures 7-17a through 7-17d show the extrapolations made to obtain in-air SPLs which would produce TTS_2 values equivalent to those resulting from their respective underwater SPLs for the four subjects in the Smith and Wojtowicz experiment. The results of these extrapolations are summarized in Table 7-11. The last column in this table shows that the SPL differences fall in the range of 25.7 to 46.4 dB for the frequencies indicated--the overall average difference is 34.1 dB. It is noted that Diver C, who exhibited the largest difference (46.4 dB), had large TTSs in water *and* in air, with rather flat recovery functions for both media. There were some audiometric questions for this subject. The audiogram taken 24 hours after the in-air exposure showed "an inexplicable change from his previous tests of from 12 to 27 dB in his left (test) ear at frequencies above 2000 Hz and a 12 and 10 dB loss in his non-exposed ear at 4000 and 8000 Hz, respectively." Nevertheless, even including Diver C, the differences between underwater and in-air hearing calculated from the data of Smith and Wojtowicz are significantly less than the differences based upon the past experiments on underwater thresholds of audibility.

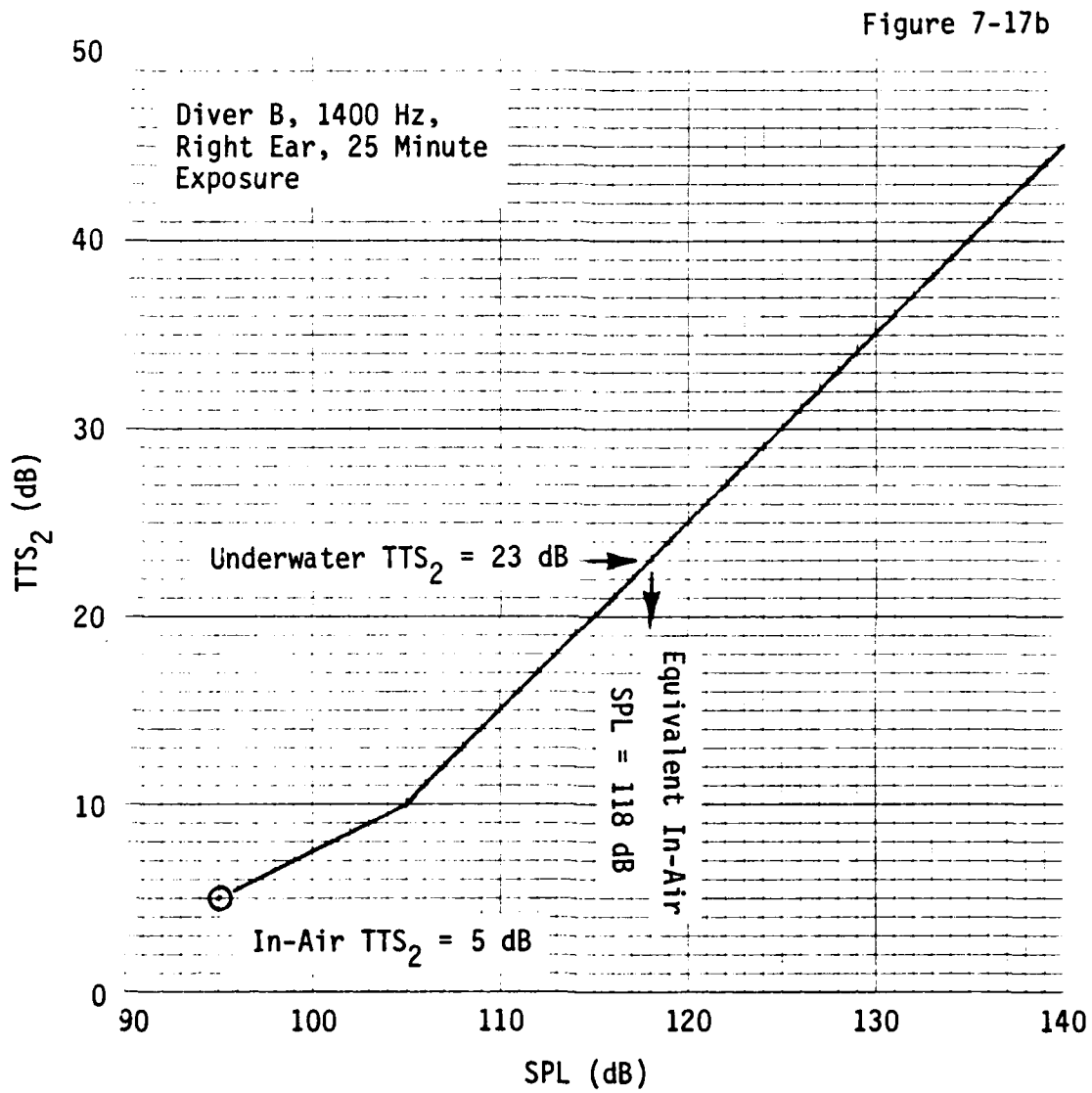
7.6.3 Summary of the Results from the Various Suprathreshold Experiments-- Are Current Underwater Sound Pressure Level Limits in Error by as Much as 30 dB?

Figure 7-18 shows the SPL differences between underwater and in-air hearing plotted versus frequency for the various suprathreshold experiments which have been described. These include the equal loudness tests and acoustic reflex tests performed by this laboratory (see Tables 7-8 and 7-7), Montague and Strickland's tolerance limit experiment (possible range of values), and Smith and Wojtowicz's TTS experiment (see Table 7-11). Montague and Strickland's data were more qualitative than quantitative since they did not actually measure *tolerance limits*, *oculo-gyral effects*, or *feeling thresholds* in air for the subjects employed underwater. Ignoring their data for the moment, which are represented by the bar in Figure 7-18, an overall average can be calculated for the remaining individual data points. This average is 36.9 dB. (One can not help but notice that this number is suspiciously close to the impedance (ρc) difference between air and water, which possibly may have some significance. It is also close to a

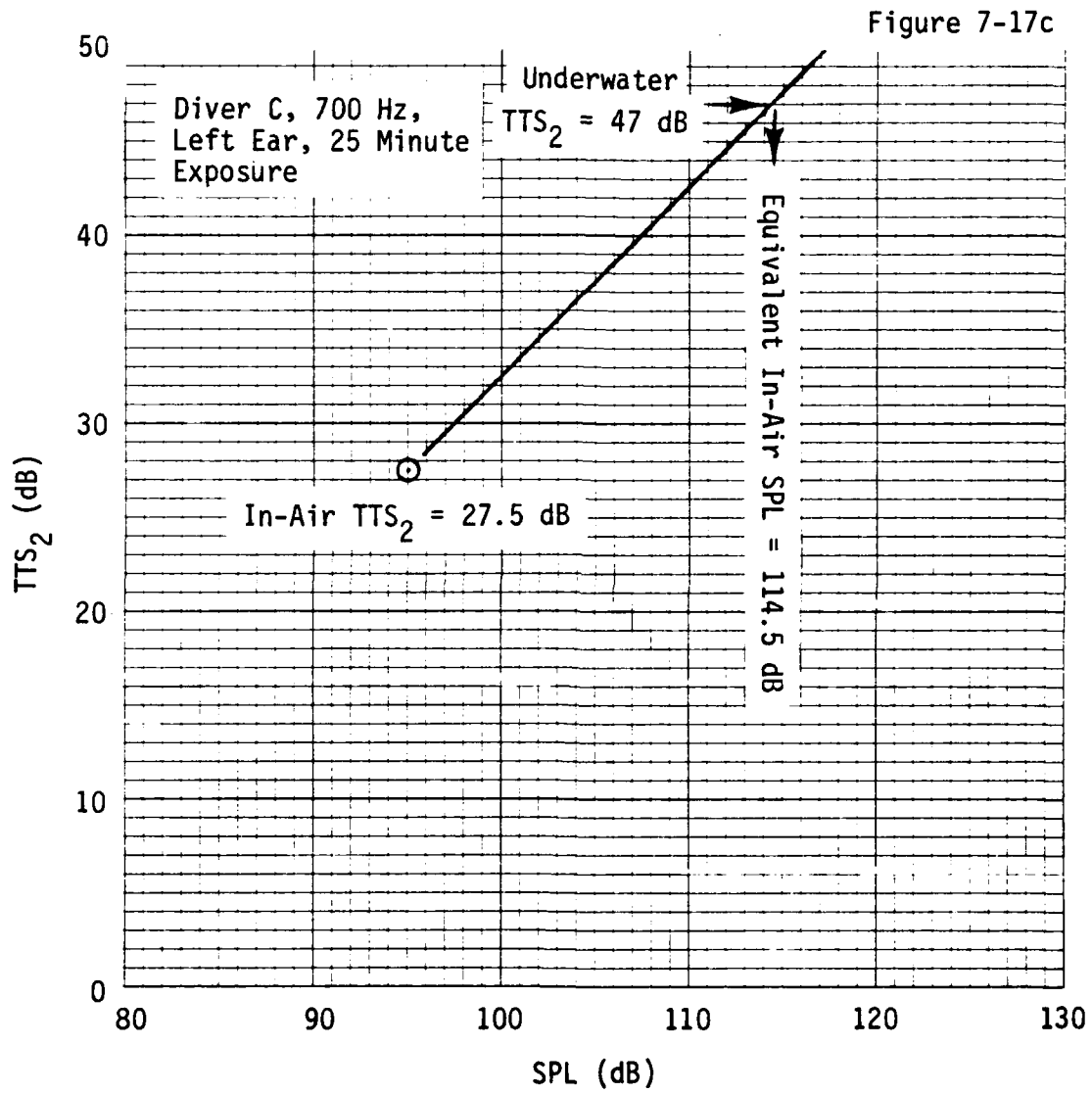


Figures 7-17a through 7-17d

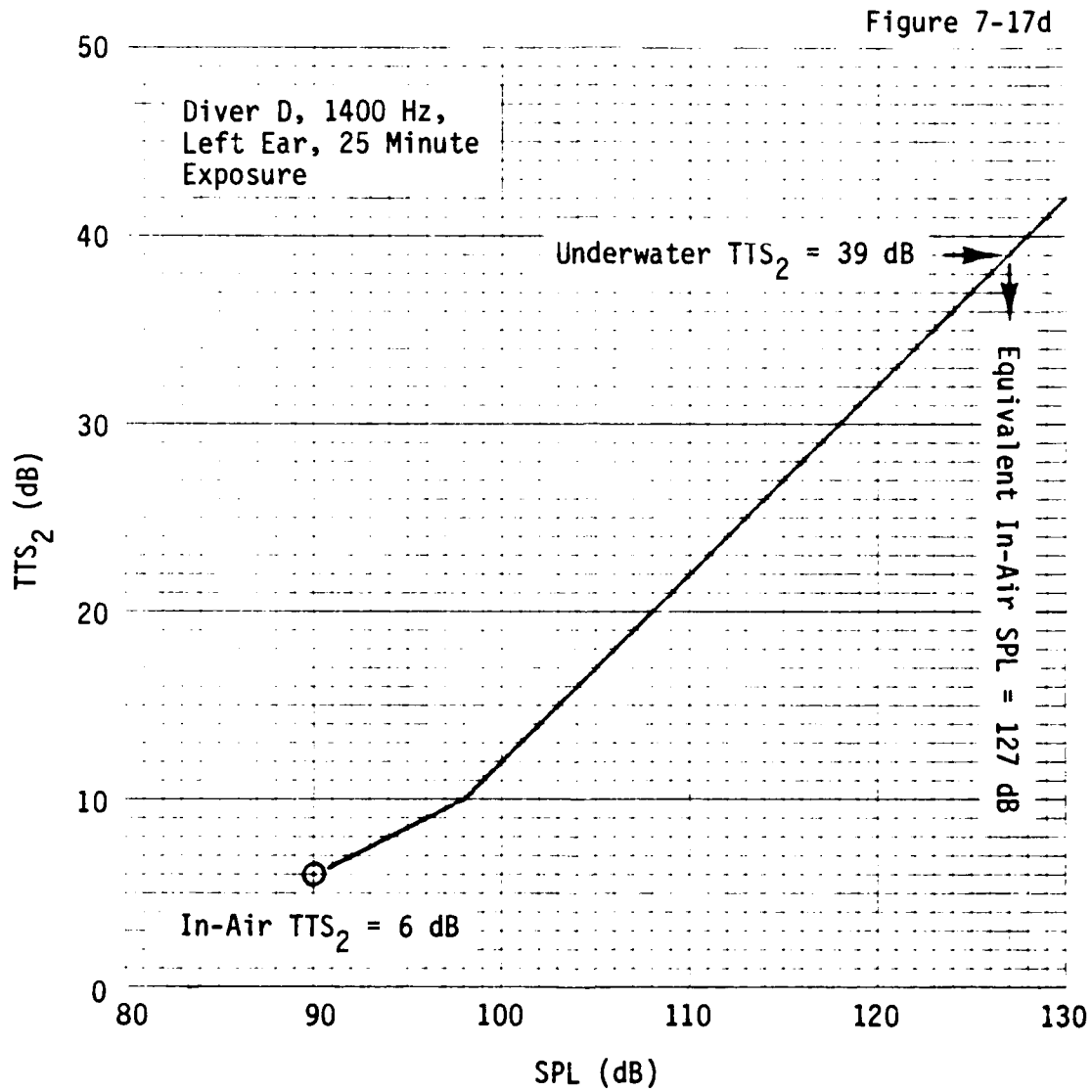
Extrapolation of in-air TTS_2 values obtained by Smith and Wojtowicz (1985) to higher SPLs using the relationship between TTS and SPL provided by Kryter (1985). The in-air SPLs that would produce the same TTS_2 values in air as were produced by the underwater exposures are indicated by the arrows.



Figures 7-17a through 7-17d (Continued)



Figures 7-17a through 7-17d (Continued)



Figures 7-17a through 7-17d (Continued)

Table 7-11. Comparison of SPLs producing equivalent TTS_2 values for underwater exposures and in-air (extrapolated) exposures. Based upon the experiment of Smith and Wojtowicz (1985).

Subject	Freq (Hz)	Average Underwater SPL (dB)	Underwater TTS_2 (dB)	Equivalent In-Air SPL (dB)	SPL Difference (dB)
Diver A	5600	165.1	36	135.0	30.1
Diver B	1400	143.7	23	118.0	25.7
Diver C	700	160.9	47	114.5	46.4
Diver D	1400	161.3	39	127.0	34.3

Note: Extrapolations of the measured in-air TTS_2 values to higher SPLs are based upon Kryter (1985), pages 246-254.

number that one might expect for improved bone conduction hearing caused by better coupling when immersed in the water medium.) The individual data points do not seem to suggest any significant upward or downward trend as a function of frequency, at least up to 5600 Hz. They appear to be fairly equally distributed above and below the calculated *average* value which has been added to the figure. The average also falls within Montague and Strickland's *range of values*.

Also shown in Figure 7-18 is a curve representing the assumed differences between in-air and underwater hearing used by the U.S. Navy for establishing underwater sound pressure level limits for divers (bareheaded or hooded--not dry helmeted). These differences are based upon underwater thresholds of audibility from Brandt and Hollien (1967) and in-air thresholds from ISO R226-1961. (Source: Chief, Bureau of Medicine and Surgery letter BUMED-3C21:NAD:slb, 6420, 5 July 1982 to Commander, Naval Sea Systems Command (SEA-00C), subject: Underwater Sound Pressure Level Limits; and Naval Submarine Medical Research Laboratory Memorandum from P. Smith to Lt. D. Styer, Navy Experimental Diving Unit dated 30 July 1982, subject: Underwater Sound Pressure Level Limits.) It appears that discrepancies as large as about 33 dB may exist between the Navy's permissible sound pressure level limits and the limits that would be established based upon the suprathreshold experiments. This is a significant difference and, therefore, it is strongly recommended that a complete series of suprathreshold tests be conducted as soon as possible in order to provide a strengthened statistical base for establishing new underwater SPL limits. It is further recommended that, in the interim, current exposure limits be modified to reflect this problem.

In conclusion, the combined evidence of our work and the Smith and Wojtowicz experiment (which probably should have raised a red flag at the time) *strongly suggest that the current underwater sound pressure level limits are invalid and err on the unsafe side by significant amounts*. Given the lack of any other quantitative suprathreshold data, it is recommended as an *interim* measure that the average value of 37 dB shown in Figure 7-18 be used as the SPL difference between underwater and in-air hearing for the establishment of *revised* underwater sound pressure level limits. The single value would apply at all frequencies of interest until such time that sufficient statistical data become available to establish the actual frequency dependence (if any). Such a revision represents a potentially serious change for ship husbandry work. However, there are compensating factors which will still allow the underwater work with noisy tools to be accomplished.

- APL-UW equal loudness tests.
- + APL-UW acoustic reflex tests.
- ◇ Estimates derived from Smith and Wojtowicz (1985), TTS experiment.
- I Montague and Strickland (1961): range of values based upon tolerance limits, oculo-gyral effects, and feeling thresholds.

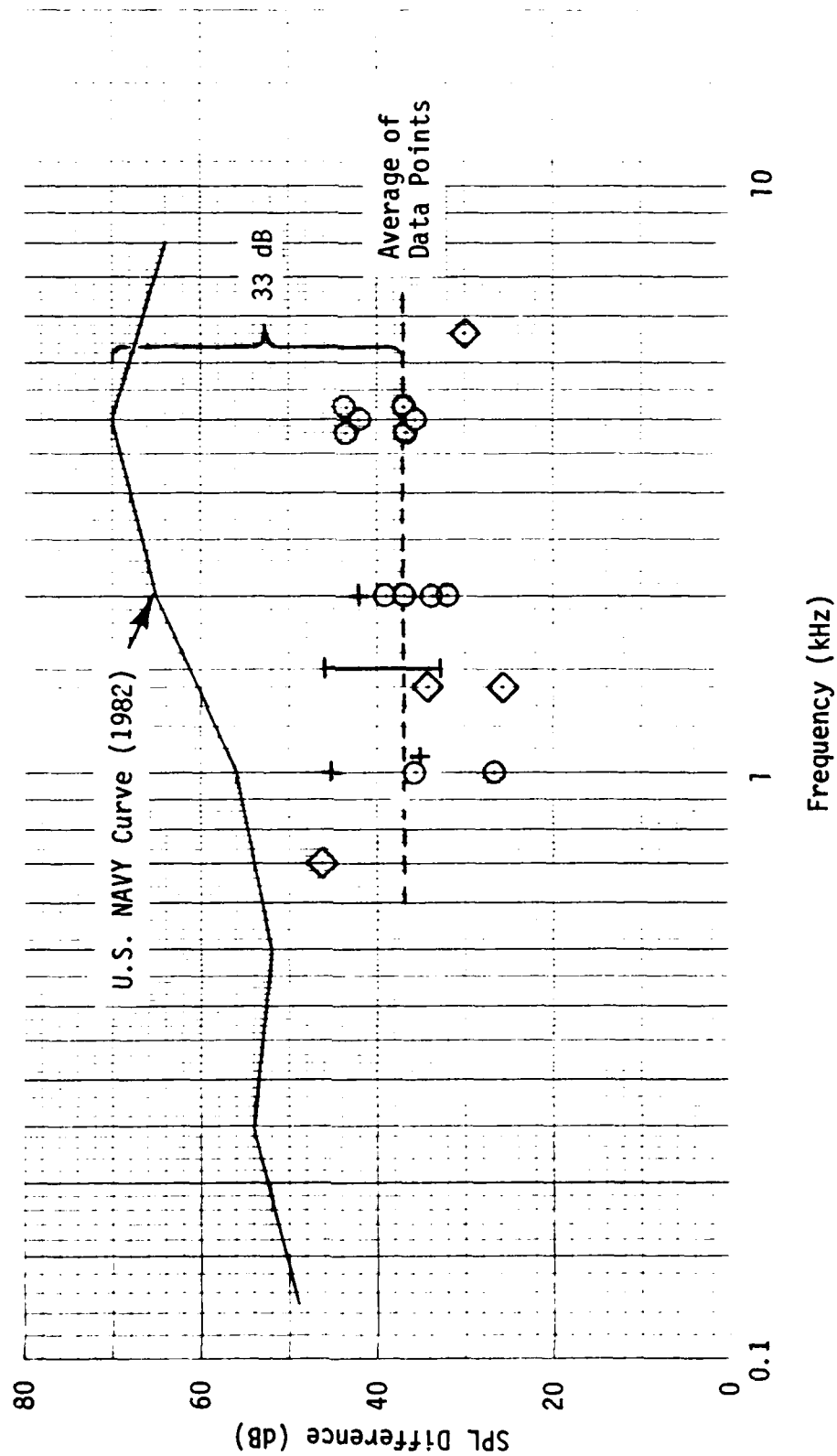


Figure 7-18

Sound pressure level differences between underwater and in-air hearing determined from four suprathreshold experiments compared with a U.S. Navy reference curve circa 1982.

First and foremost, foam neoprene diving hoods definitely provide protection against underwater noise at frequencies above 500 Hz and to depths of at least 30 ft (and probably to 100 ft) as discussed in Section 6 of this report. (Dry helmets can also provide protection from external in-water noise, but they have their own internal noise problems which need to be solved.) Credit must be allowed for the attenuation provided by diving hoods or one will be unable to work for any reasonable length of time with the noisier tools. The Chief, Bureau of Medicine and Surgery letter of 5 July 1982 (BUMED-3C21:NAD:slb 6420) does *not* allow for hood attenuation. Since underwater hearing is by bone conduction, the skull needs to be protected in high level noise fields, and it would probably be wise also to wear a foam neoprene diving suit to protect the torso and reduce internal sound transmission from the body to the skull.* As indicated in the conclusions of Section 6 of this report, a *conservative* estimate of hood attenuation, pending the collection of additional supporting data, is 20 dB at 1 kHz and above and zero loss below 1 kHz. It is recommended that these values be used in establishing noise exposure limits as an interim measure. For protection purposes, hoods must be well fitting and in good condition. It would be prudent to use hoods having a minimum thickness of 3/16-in.

A second compensating factor is the use of A-weighting. The BUMED letter of 5 July 1982 deleted A-weighting in the guidelines for determining underwater sound pressure level limits. As indicated in Section 8 of this report, the use of A-weighting "de-emphasizes low and very high frequencies because they are, for a given SPL, less hazardous to hearing. This should be as true underwater as in air, after correction for less efficient sound transmission to the human ear." Therefore, the A-weighting factor should be retained in the determination of noise exposure limits. This will be of benefit for underwater work because it allows higher noise levels at the low and high frequency ends of the audio range.

Another factor that must be considered is the role of the acoustic reflex in the underwater environment. Loud sounds elicit a reflex contraction of the middle ear muscles which in air serves to attenuate sound transmission into the cochlea at lower frequencies. Although data are sparse, there appears to be little or no reflex attenuation in air above 1500 Hz. Our concern, therefore, is at frequencies below this value. In water, the

*Sound transmission from the torso to the skull may *not* be a significant problem. Further experimental work in this area could be conducted to resolve this question.

attenuation provided by this reflex is effectively bypassed because of bone conduction and, therefore, a given SPL increase above reflex threshold in water will be more hazardous than the same increase in air. It is proposed that this problem be handled by special spectral weighting in the low frequency region as described in Section 8.6 of this report. (Section 8 describes a new approach for developing an underwater noise exposure standard.) The adjustment at any given frequency will be made only when the SPL exceeds the reflex threshold, and its value will vary with increasing SPL. Unfortunately, because the reflex does not protect the ear underwater, exposure limits will have to be more restrictive if the sound from a given tool contains high level spectral components of low frequency (below 1500 Hz) noise.

8. A PROPOSAL FOR AN UNDERWATER NOISE EXPOSURE STANDARD (air-supplied bare-headed diving)

8.1 Introduction

There are, in principle, several methods by which an underwater noise exposure standard could be developed. The ideal would be an epidemiological study, comparing hearing sensitivity in non-noise exposed divers of different ages to divers who had known noise exposures. This approach has been useful in developing (and especially, validating) standards for noise exposure in air, but no data of this type are available for underwater exposure. An attempt to acquire such data would probably fail because of the unavailability of subjects with stable, well-characterized underwater noise exposures.

A second method assumes that brief exposures causing equal amounts of temporary threshold shift (TTS) will, over time, cause equal amounts of noise-induced permanent threshold shift (NIPTS). This approach was important in the development of the damage risk criteria published by the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) of the National Research Council (Kryter *et al.*, 1966). These criteria, while not explicitly adopted, were influential in the development of the noise exposure limits eventually promulgated by the U.S. Occupational Safety and Health Administration (OSHA). However, there is considerable doubt that TTS predicts NIPTS well, and sufficient data on underwater TTS are not available, in any case, to support standards development.

We propose a third alternative, in which existing standards for noise exposure in air are extrapolated to the underwater environment, correcting for the reduced audibility of underwater sound. We assume that the mechanisms of injury leading to NIPTS are the same underwater as in air, that the relative damaging potentials of different frequencies are the same in both media, and that, for a dynamic range of at least 70 dB, equal level increases above threshold cause equal changes in behavioral and electrophysiological measures in both media. Slightly below the intensity range where damage risk begins, the acoustic reflex is activated, yielding a graded response which, in air, attenuates transmission of low-frequency sound to the cochlea. In water, the reflex still occurs, but is ineffective in attenuating the primarily bone-conducted sound; this factor will be taken into account in our proposed exposure standard.

This section of the report was written by Robert A. Dobie. Information for integrating this section with the rest of the report provided by Paul C. Kirkland.

This proposal is intended to apply to a bare-headed diver breathing air in shallow water, and exposed to continuous noise, as defined in OSHA and NAVMED regulations. Modifications for the use of diving hoods can be made as discussed in Section 6 of this report. Modifications possibly appropriate for hyperbaric conditions, depth diving, and different gas mixtures will be treated at a later time. Impulse noise will be briefly discussed.

8.2 Hearing in Water and Air

Studies on behavioral threshold differences (air vs water) have given conflicting results, as discussed in Section 5 of this report. There are several sources of uncertainty and possible error. First, most authors have tested small numbers of subjects. Second, acoustic calibration for free-field studies is complex for both air and water. Third, most aquatic environments have low-frequency ambient noise which is difficult to control and may cause behavioral thresholds to be spuriously elevated. Fourth, the hearing sensitivities of the subjects have not always been clearly defined. For the purpose of *illustration* in this proposal, we will use the corrected underwater threshold data discussed in Section 5.10 and summarized in Figure 5-33. Thresholds in air will be taken from an international standard (ISO R226-1961), with Killon's *corrections* (Figure 4-1). As discussed in Section 7 of this report, threshold values lower than those illustrated in Figure 5-33 may be required in the final application to an underwater noise exposure standard. Therefore, we will *also provide an illustration* using the 37 dB interim value proposed in Section 7.6.3 as the difference between underwater and in-air hearing.*

Using the two sets of *threshold* data (each in dB SPL), one can calculate, for each spectral region, a difference score representing the relative loss of sensitivity of the human ear in water. Because of the masking effects of ambient noise on threshold determination in water, it would be desirable to have comparative data for *suprathreshold* performance in air and water (e.g. acoustic reflex thresholds or uncomfortable levels) but, except for the work described in Section 7 of this report, these appear to be unavailable. Smith *et al.* (1970) measured TTS after 3500 Hz exposure at various levels in air and

*It has been recommended in Section 7 that the average value of 37 dB shown in Figure 7-18 be used as the SPL difference between underwater and in-air hearing for the establishment of revised underwater sound pressure level limits, pending the collection of additional suprathreshold data.

water, and found that, for equivalent TTS, underwater levels were 68 dB above air levels. However, different subjects were used for the in-air TTS measurements than for the in-water measurements. Because of wide intersubject variability in the development of TTS, their results can be questioned. Smith and Wojtowicz (1985) extended these observations. Based on *their* very few measurements, one could only conclude that air-water differences re equivalent TTS had to be significantly *less than* 66 dB (700 Hz), 56 or 71 dB (two subjects, 1400 Hz), and 65 dB (5600 Hz). (See Section 7.6.2.2 for a more complete discussion and interpretation of the Smith and Wojtowicz experiment.) Especially for low frequencies, TTS experiments at high sound levels may underestimate air-water threshold differences at intermediate sound levels. This is because the acoustic reflex attenuates sound in air but not in water.

8.3 Acoustic Reflex Attenuation

Loud sounds (above about 85 dB sensation level for monaural tones) elicit a reflex contraction of the middle ear muscles (in man, primarily the stapedius, which is innervated by the facial nerve), which attenuates sound transmission into the cochlea. This attenuation is greatest for low frequencies; transmission is unaffected or even enhanced for high frequencies, as could be expected as a mechanical consequence of stiffening the ossicular chain. In experimental animals, the amount of attenuation can be assessed fairly directly by cochlear microphonic recordings (Møller, 1965). Tetanic stimulation of the stapedius muscle in anesthetized cats resulted in cochlear microphonic attenuation of 15 dB at 500 Hz, and 8 dB at 1000 Hz (Starr, 1969). More indirect methods have been required in man; as seen in Table 8-1, only scanty data are available.

Reger (1960) measured threshold shifts in eight subjects who could *voluntarily* elicit a sustained middle ear reflex. His data may well over-estimate the amount of attenuation occurring under physiologic conditions (he acknowledged that his subjects probably had prominent tensor tympani contraction, for example). However, they are still valuable in placing a probable upper limit; note that there was no threshold shift for 2000 Hz or higher frequencies. In addition, they suggest that reflex attenuation may be relatively flat for low frequencies (125-500 Hz).

Borg and his co-workers (Borg, 1968; Borg and Zakrisson, 1974; Zakrisson, 1975) studied acoustic reflexes in patients with acute facial nerve paralysis (Bell's palsy). These patients had absent stapedius reflexes on the side of the paralysis, so that loud sounds could be transmitted into the cochlea without the usual attenuation. They estimated the amount of attenuation which had been lost by measuring acoustic reflexes

Table 8-1. Attenuation in dB due to acoustic reflex activity in man.

Study	Frequency (Hz)							
	125	250	500	1000	1500	2000	4000	8000
Reger, 1960 ¹	33	38	34	16			2	2
Borg, 1968 ²			12-15		0-6			
Borg and Zakrisson, 1974 ³			19					
Morgan and Dirks, 1975 ⁴			7					

¹8 ears capable of *voluntary* middle ear muscle activation.

²4 Bell's palsy cases; attenuation estimated by shift in reflex amplitude-intensity functions (contralateral), re post-recovery status, at 20 dB re reflex threshold.

³19 Bell's palsy ears, same method as #2, but measured at 30 dB re reflex threshold.

⁴Attenuation estimated by loudness comparison with and without prior reflex activation.

on the *unparalyzed* side, elicited by loud sounds presented to the *paralyzed* side, both before and after recovery from paralysis. Reflex threshold was unaffected by facial nerve paralysis, but the *amplitude* of reflex contraction contralateral to the stimulated ear grew more rapidly when the ipsilateral stapedius was paralyzed. Comparing amplitude-intensity curves, they reasoned that equivalent contralateral reflex amplitudes would be elicited by sounds of equivalent sensory magnitude on the stimulated side. Thus, the amount of lateral shift between the amplitude-intensity curves should represent the amount of attenuation normally afforded by the acoustic reflex. This attenuation was found to increase with increasing stimulus level at a rate of about 0.6 dB/dB above reflex threshold. Thus, reflex attenuation was a graded phenomenon, reaching a maximum, for 500 Hz, of 19 dB for a stimulus 30 dB above reflex threshold. Using the same technique, Borg (1968) found minimal reflex attenuation (0-6 dB) for 1450 Hz. It is possible that these data from Bell's palsy patients fail to accurately represent physiological reflex attenuation, since the tensor tympani is unaffected and since Bell's palsy may affect the VIIIth (auditory) nerve as well as the VIIth (facial) nerve (Rosenhall *et al.*, 1986). However, auditory nerve involvement would be expected to reduce the afferent input to the brainstem, resulting in a reduced contralateral reflex effect for a given input level. This is the opposite of what Borg and his colleagues found and it suggests that if anything they may have *underestimated* reflex attenuation. In addition, one cannot be certain that all patients recovered stapedius function completely, but again, this would have led them to underestimate reflex attenuation.

A contrary view is expressed by Morgan and Dirks (1975) who inferred only a 7 dB reflex attenuation at 500 Hz in a psychophysical experiment in which they compared the loudness of sounds presented with and without a preliminary reflex-eliciting sound.

It seems reasonable to conclude that there is little or no reflex attenuation in man above 1500 Hz, although even this is based on very few data. For 500 Hz, the most conservative assumption (most protective for the diver's ear) is that Borg and Zakrisson are right regarding the magnitude of reflex attenuation. Further, one must assume that this effect is absent underwater. Even if underwater hearing involves a tympanic or dual-path mechanism for certain frequencies, the bone-conduction pathway is readily available and would be unaffected by reflex muscle contraction (complete stapes fixation by otosclerosis causes only a minimal bone conduction loss, greatest at 2000 Hz (Carhart, 1950)).

8.4 Acoustic Reflex Protection

The view is commonly expressed (e.g., Tonndorf, 1976) that the acoustic reflex decays rapidly under constant stimulation and can therefore be of little protective use. Fletcher and King (1963) found that while TTS induced by impulses could be reduced by presenting a reflex-activating tone prior to each impulse, stapedectomized patients (whose stapedius muscles have been cut) have no increased TTS re normals. However, their stapedectomy patients had worse hearing than their control group to begin with, nullifying the comparison.

While reflexes to constant high-frequency tones decay quickly, low-frequency tones and especially complex stimuli elicit reflexes decaying over several minutes. More importantly, very slight changes in spectrum and/or intensity (as typically occur in real-world occupational exposures) rapidly reactivate the reflex. Nilsson *et al.* (1980) reviewed the data supporting these assertions, and showed that there was negligible reflex decay for a 30-minute exposure to taped factory noise at 97 dBA.

Bell's palsy once again provides a human model for the study of reflex protection. Zakrisson (1975) found that TTS was increased for 500 Hz, but not for 2000 Hz, in 22 ears with paralyzed stapedius muscles, compared to the contralateral control ears. Zakrisson *et al.* (1980) extended these observations to exposures to real-world factory noise (102 dBA x 15 min), and found that, compared to control ears, Bell's palsy ears displayed TTS that was more severe (15 dB vs 7 dB maximum), and involved a much wider frequency range (750-8000 Hz vs 1500-6000 Hz).

We are unaware of any data comparing PTS in human ears unprotected by the acoustic reflex to normal ears. However, Borg *et al.* (1983) showed that rabbit ears deprived of acoustic reflex protection suffered an increased amount of PTS, over a wider frequency range, compared to normal ears similarly exposed.

The scanty data available seem to indicate that for complex and time-varying exposures, the reflex is indeed protective.

8.5 Acoustic Reflex Threshold

Acoustic reflex output - usually assessed as an impedance change rather than by direct measurement of muscle activity or sound attenuation - grows in a sigmoid fashion as input sound levels increase. Nevertheless, the mid-portion of the input-output curve is typically roughly linear over about a 30 dB range (Dallos, 1964). Reflex threshold is most often defined as the lowest sound level for which an impedance change can be detected, but there is considerable variability in such threshold estimates, due to poor signal-to-noise ratios. In addition, especially for noise signals, the first part of this S-shaped curve is very flat, with little impedance change for about the first 10 dB of input above threshold (Gelfand and Piper, 1981; Morgan *et al.*, 1977).

We would like to know the point at which the reflex begins to *substantially* attenuate input to the cochlea (for in-air sound); for this purpose the best "threshold" estimate is obtained by extrapolating the linear part of the input-output curve to intersect zero output. (In so doing, we model the input-output curve as a straight line). Unfortunately, complete curves are rarely available in the literature.

In reviewing available reports, we must also keep in mind that almost all acoustic reflex threshold data refer to the *monaural, contralateral* paradigm. Reflexes elicited by sounds presented binaurally are typically 5-10 dB more sensitive (input-output curves shifted to the left) than contralateral reflexes (Møller, 1962a). Similarly, as will be seen, thresholds are systematically lower (re dB SPL) as stimulus bandwidth increases (Popelka *et al.*, 1974).

Since the acoustic reflex attenuates sound transmission only for frequencies below about 1500 Hz, we will consider only this frequency range. Mean reflex thresholds for 1000 Hz tones are typically reported to be 87-91 dB SPL, with 500 Hz thresholds in the 90-93 dB SPL range (Møller, 1962b; Silman, 1979; Popelka *et al.*, 1974; Gelfand and Piper, 1981). Møller (1962) offers scanty data at 250 Hz (about 107 dB SPL), and suggests that the reflex threshold curve parallels behavioral thresholds (as a function of frequency).

Reflex thresholds for white noise are much lower: 70-80 dB SPL (Dallos, 1964; Popelka *et al.*, 1974; Morgan *et al.*, 1977; Silman, 1979; Margolis *et al.*, 1980; Gelfand and Piper, 1981). While there is considerable variation across studies, some of this is due to the fact that the input-output curve initially rises quite slowly for noise stimuli, making

threshold estimation difficult. Two studies present complete input-output curves, (Dallos, 1964; Morgan *et al.*, 1977); in both cases, extrapolation of the linear part of the curve yields a threshold of 75-80 dB SPL.

Varying stimulus bandwidth between tones and white noise yields intermediate thresholds. Møller (1962a) states that for bandwidths up to about an octave, reflex thresholds for noise are 4-5 dB lower than for tones. Popelka *et al.* (1974) found the reflex threshold for a 1.5 octave-noise band centered at 1 kHz to be 9 dB less than for a 1-kHz tone. Two studies compared reflex thresholds for narrow-band noise (0.5 to 1.0 octave) and white noise (Margolis *et al.*, 1980; Richards and Goodman, 1977); threshold differences were 6-13 dB, in favor of white noise.

Reflex thresholds for 500 Hz narrow band noise have been reported to be 92.5 dB SPL (Richards and Goodman, 1977; 0.5 octave) and 75.9 dB SPL (Peterson and Liden, 1972; 2.0 octave). 1000 Hz noise thresholds are reported to be 87.0 dB SPL (Richards and Goodman, 1977; 0.5 octave) and 77.3 dB SPL (Peterson and Liden, 1972; 0.9 octave).

For underwater hearing conservation purposes, we would like to imagine a sound level meter which would independently treat octave bands of noise. For low intensities in each band, output would rise linearly (slope = 1 dB/dB) with input, after correcting for air-water audibility differences and A-weighting. Above reflex threshold, input-output curves would rise more steeply (for low frequencies), compensating for the reflex attenuation which is missing underwater.

Unfortunately, there is little direct information, as reviewed above, on reflex thresholds for octave bands of noise. At 1 kHz, we have a direct estimate of 77.3 dB SPL (0.9 octave noise); this fits nicely between thresholds for white noise and pure tones. However, assuming a sigmoid input-output function with an initial low-slope portion, a better estimate for the linear part of the curve would be 85 dB SPL (by analogy to the situation for white noise).

At 250 and 500 Hz, no data for octave-band noises were found. It seems most reasonable to assume that these thresholds would be about 10 dB worse than for white noise, i.e., about 85-90 dB after correction for air-water differences and for A-weighting. Subtracting 5-10 dB to correct for the greater sensitivity of the binaurally-elicited reflex would yield octave band reflex thresholds around 80 dB.

8.6 Spectral Weighting

OSHA and NAVMED regulations for occupational noise exposure (as well as the regulations of most industrial nations) specify the use of the "A-scale" of the sound level meter (ANSI S1.4-1961). This set of spectral weights de-emphasizes low and very high frequencies because they are, for a given SPL, less hazardous to hearing. This should be as true underwater as in air, after correction for less efficient sound transmission to the human ear. Our proposal is to generate a new set of spectral weights for use in underwater noise exposure studies ("dBU?"). These weights would incorporate the A-scale weights, along with the air-water sensitivity differences, as illustrated in the examples presented in Table 8-2. Table 8-2a uses the "better" experimental data for underwater audibility thresholds presented in Section 5 of this report (see Figure 5-33). Table 8-2b uses the water-air hearing difference recommended in Section 7 which is based upon available suprathreshold data. The differences between the weights derived by the two methods are small for frequencies below 1000 Hz but become large above this frequency (e.g., 29 dB at 4000 Hz). (Based upon the arguments presented in Section 7, we would recommend that the later set of weights be used at this time.)

We propose that, beginning at 80 dBU, output (dBU) should increase more rapidly than input (dB SPL), at low frequencies. The slopes of the "reflex compensation" portions of these curves should be equal to $1/1-a$, where a = reflex attenuation (dB/dB) for a given frequency. Based on data previously reviewed from Borg and his co-workers, $a = 0.6-0.7$ for 500 Hz (and probably for lower frequencies as well). Allowing for the possibility of some reflex fatigue/decay, we propose that a be set at 0.5 for the octave bands centered at 125, 250, and 500 Hz, and at 0.25 for the 1000 Hz band ($a = 0$ for higher frequencies). The corresponding slopes of the dBU output function would be 2.0 and 1.33, over a 30 dB dynamic range in dBU.

For the sake of *illustration only*, let us use the data of Table 8-2a. Consider, for example, the 500-Hz band. Air-water audibility difference and A-weighting yield a dBU correction factor of -46 dB (this would be -40 dB if Table 8-2b were used). Thus a 500 Hz narrow band noise at 116 dB SPL in water would be equal to 70 dBU. This means that this sound would be as hazardous (not very) as a similar sound registering 70 dBA in air. As the level was increased beyond 126 dB SPL (80 dBU), loudness and hazard would grow more rapidly underwater than in air, because the reflex, though active, would fail to attenuate the input to the cochlea. Assuming attenuation = 0.5, a 10-dB increase underwater would be equivalent to a 20 dB increase in air. Thus, while 126 dB SPL yields 80 dBU, 136 dB SPL should yield 100 dBU, and 141 dB SPL should

Table 8-2a. Proposed derivation for spectral weighting for estimation of underwater noise hazard (for levels below acoustic reflex threshold) using air and water threshold values.

	Octave band (Hz)						
	125	250	500	1000	2000	4000	8000
Underwater threshold ¹	69	54	49	52	63	62	70
Air threshold (free-field) ²	28	15	6	4	1	-4	15
A-scale weighting ³	-16	-8	-3	0	1	1	-1
Proposed "U-scale" weighting ⁴	-57	-47	-46	-48	-61	-65	-56

Table 8-2b. Proposed derivation for spectral weighting for estimation of underwater noise hazard (for levels below acoustic reflex threshold) using suprathreshold data for estimating air-water hearing differences.

	Octave band (Hz)						
	125	250	500	1000	2000	4000	8000
Underwater versus in-air hearing difference based on suprathreshold data	37	37	37	37	37	37	37
A-scale weighting ³	-16	-8	-3	0	1	1	-1
Proposed "U-scale" weighting ⁴	-53	-45	-40	-37	-36	-36	-38

¹See Figure 5-33.

²See Figure 4-1.

³From ANSI S1.4-1961.

⁴For each octave band,

$$W_u = W_a - (\theta_u - \theta_a)$$

Where

W_u = proposed "U-scale" weighting

W_a = A-scale weighting

θ_u = underwater threshold

θ_a = air threshold (minimum audible field)

yield 110 dBU. Since the acoustic reflex dynamic range in air is only 30 dB, we only need to compensate for its absence over that range, in terms of dBU output. Above 141 dB SPL, dBU again grows at a rate of 1 dB/dB. Figure 8-1 shows this graphically.

8.7 Permissible Exposure Level and Duration

Table 8-3 shows how individual octave-band adjusted levels (Li) would be combined to yield an overall level in "dBU." This level would be directly comparable to a level measured in air using the A-scale of a sound level meter. For NAVMED purposes it would be logical to use the same basic permissible exposure standard: 84 dB(U), for a continuous 8-hour exposure, with a 4-dB trading ratio. Agencies such as OSHA which use different permissible exposure levels and trading ratios could also use a "dBU" meter without changing the method by which dBU is calculated.

The method proposed here is similar in some respects to one proposed in a NAVMEDCOM interim standard (BUMED-3C21:NAD:slb 6420, 5 July 1982), and explained in more detail in a memo from P. Smith of the Naval Submarine Medical Research Laboratory to D. Styer of the Navy Experimental Diving Unit (30 July 1982) and in another letter from the Commanding Officer, Navy Experimental Diving Unit to NAVSEA CODE 00C (NEDU:WAE:cz 6420 Ser 404, 29 October 1982). (See appendices to this report for copies of these documents.) The differences are the inclusion of A-scale weighting and corrections for missing acoustic reflex attenuation, plus a new set of values (which may be revised further--see Section 7) for air-water threshold differences. The NAVMEDCOM approach is based on the assumption that "noises of equal sensory magnitude are equally hazardous to the ear." But their method does not yield "sensory magnitude" or sensation level; rather, it yields an "equivalent SPL." Only by including A-scale weights or their equivalent and the effects of the acoustic reflex can this be corrected to something like "sensory magnitude."

8.8 Problems and Issues

Obviously, the data used to derive the "U-scale" weights can be criticized. Different underwater thresholds could be used, as could different minimum audible field (air) thresholds. More data on the magnitude of acoustic reflex attenuation for different frequencies would surely be welcome. The paucity of good data in these areas strongly suggests that, even if a standard like the one proposed here is adopted, the Navy would probably be wise to enroll all noise-exposed divers in hearing conservation programs and

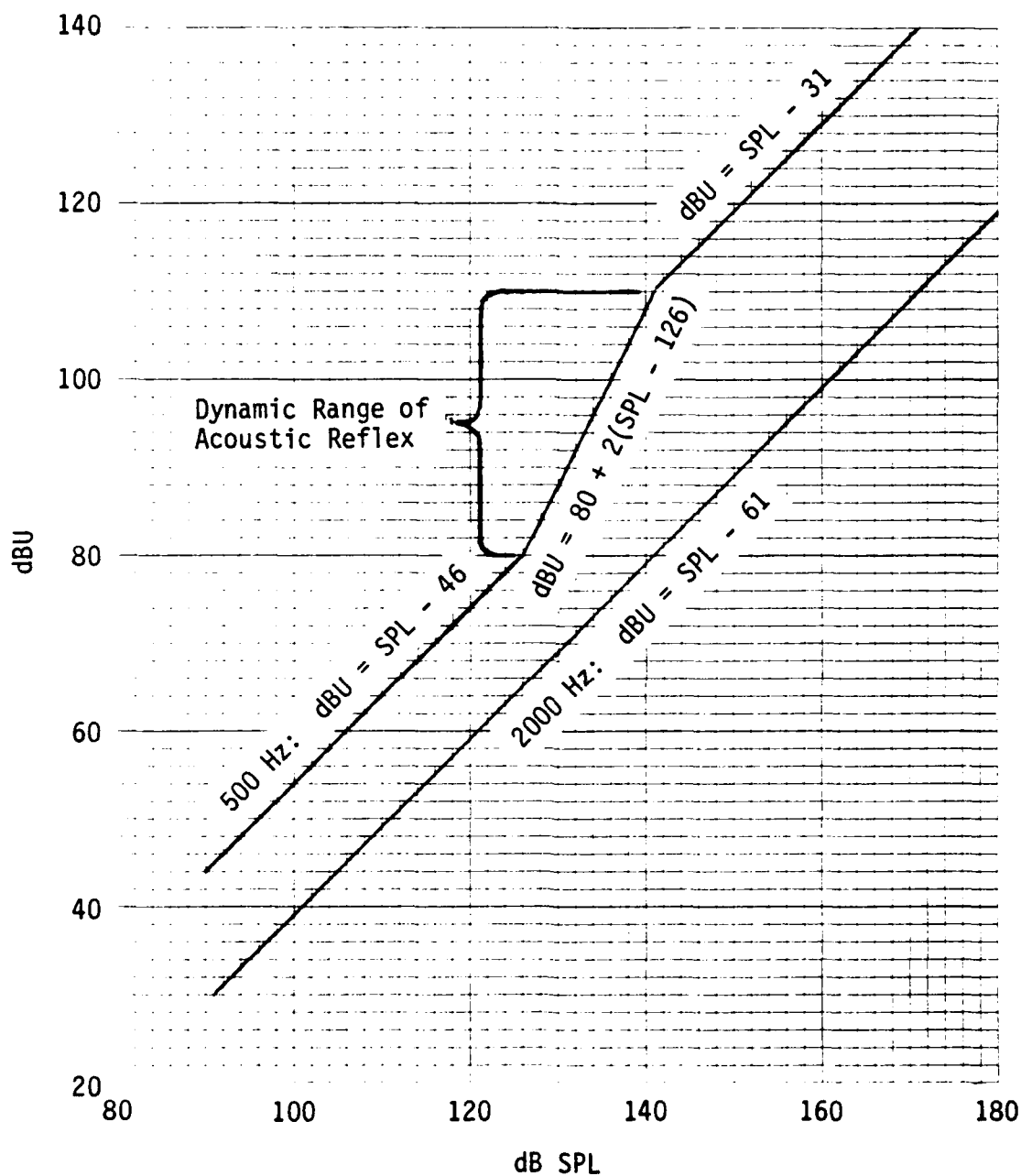


Figure 8-1

Example of proposed relationship between underwater sound pressure level (dB SPL) and equivalent dBU value for frequencies of 500 Hz and 2000 Hz. For an octave band centered at 1000 Hz, the slope over the dynamic range of the acoustic reflex would be 1.33. (This figure is based upon the spectral weighting given in Table 8-2a. A similar figure can be drawn using the spectral weights of Table 8-2b.)

Table 8-3. Method for calculation of exposure level and permissible duration.

1. For each octave band, $L_i = \text{SPL} + W_u$.

2. Overall effective level (L) :

$$L \text{ (dBU)} = 10 \log_{10} (\sum 10^{L_i/10}) .$$

3. Permissible exposure time (hrs):

$$T = \frac{8}{2^{\frac{L-84}{4}}}$$

(See text for discussion)

begin to collect systematic epidemiologic data linking NIPTS to various noise exposure levels.

It would be very useful (if feasible) to study acoustic reflexes underwater (contralateral to the ear receiving acoustic input). Do their amplitude-intensity functions show abnormally steep slopes, as seen in Bell's palsy patients? This would corroborate our proposed approach, and the magnitude of shift for different intensities above reflex threshold would permit a more valid estimate of the slopes of the "reflex compensation" parts of the dBU input-output functions.

A comparison of acoustic reflex thresholds underwater and in air, for different frequencies, would be a valuable addition to the *controversial* data base on air-water audibility differences. Ambient noise would not be a problem; in fact, should air-water reflex threshold differences be smaller than the behavioral threshold differences, this would tend to cast doubt on the latter data as probably contaminated by ambient noise problems underwater. Complete reflex input-output functions for octave-band noises would help to determine appropriate thresholds for "reflex compensation" in dBU.

Do acoustic reflexes elicited by bone-conducted sound exhibit abnormally rapid amplitude growth? Does the absence of reflex attenuation cause a compressed dynamic range for bone-conducted sound, measured psychophysically? One suspects that transducer shortcomings have prevented the collection of data that would answer these questions.

A more complete mapping of TTS comparisons between air and water would be very desirable. One attractive strategy would be to follow Smith *et al.* (1970, 1985) in finding air and water sound pressure levels which, for the same duration, give identical TTS. One might expect that the air-water differences would be greater for moderate levels giving little TTS than for higher levels, at which the acoustic reflex reduces cochlear input in air.

Equal-loudness experiments (air versus water), as proposed in Section 7 (with some promising preliminary data), can be conducted rapidly. They are less affected by ambient noise than threshold experiments and should add valuable data to our estimates of air-water differences.

All of these areas of investigation (behavioral thresholds and loudness functions, acoustic reflex thresholds and growth functions, and TTS studies) could be extended to the infrasound and ultrasound regions, as far as is practical. In principle, the "U-scale" weighting scheme in Table 8-2 could be expanded to lower and higher frequencies as data become available. However, in the interim, policy should be guided by two well-accepted principles: first, if it is inaudible, it won't cause NIPTS (although vibration may interact with audible noise to *increase* NIPTS). Second, an exposure which doesn't result in TTS will not, over time, cause NIPTS (Ward *et al.*, 1976). Individual tools and devices, for example, could be considered innocuous if the sound emitted is inaudible *or* fails to produce TTS.

Since there is scant agreement on rule-setting for impulse and impact noise in air, it is to be expected that the job will be even harder underwater. There is one simplification: the acoustic reflex can be ignored since, except for rapid impulse trains or impulse/continuous noise mixtures, the reflex occurs too slowly to be of any protective value in air or water. Air-water threshold differences (Table 8-2) range from 39-66 dB (and could be lower as discussed in Section 7). It seems logical that to add say 35-40 dB to the impulse standard for air (140 dB peak level) would yield at *least* as protective a standard.

Extensions and modifications to this proposal to include hyperbaric conditions, depth diving, etc. also may be possible at a later time.

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APPENDIX A

**U.S. Navy Correspondence Related to
Underwater Sound Pressure Level Limits**

NEDU:RAS:cz

6420

Ser

90

08 MAR 1982

From: Commanding Officer, Navy Experimental Diving Unit
To: Commander, Naval Sea Systems Command (SEA-00C)

Subj: Underwater Sound Pressure Level Limits

Ref: (a) NSMRL Memo dtd 28 DEC 1981 (NOTAL)

Encl: (1) NCSC SP81-55-056 (Procedures For Noise Measurements of Diver Tools)
(2) NCSC Analysis of "Cavijet" Sound Pressure Levels

1. Presently, no BUMED approved standards exist for determining safe sound levels for divers using underwater hand tools. Enclosures (1) and (2), which comprise the "only game in town", appear reasonable and engineeringly sound and are used by NEDU in the Approved for Navy Use (ANU) process for diver tools.
2. Informal discussions with NSMRL, reference (a) germane, indicates some objections to the procedures outlined in enclosures (1) and (2).
3. It is requested that the appropriate BUMED activity be tasked to formally review and comment on enclosures (1) and (2) and/or provide an approved standard for underwater sound pressure level limits.
4. Because the NCSC guidance, enclosures (1) and (2), appear safe and reasonable in evaluating acoustical hazards to divers, NEDU plans to continue to apply these guidelines to the ANU process for diver tools until such time as an approved standard is provided.

R. A. BOPHOLDT

Copy to:
BUMED
BUMED (Code 302)
NCSC
NCSC (Code 715)
NARS (Code 41)
NSMRL
NCEL



DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20352

IN REPLY REFER TO

OOC/SAD

5100

Ser 461

12 APR 1982

From: Commander, Naval Sea Systems Command
To: Chief, Bureau of Medicine and Surgery (BUMED 03C2)

Subj: Underwater Sound Pressure Level Limits

Ref: (a) CO, NEDU ltr NEDU:RAB:cz 6420 Ser 90 dtd 18 Mar 82

Encl: (1) NCSC SP81-55-056 (Procedures for Noise Measurements of Diver Tools)
(2) NCSC Analysis of "Cavijet" Sound Pressure Levels dtd Jun 80

CO	<i>[Signature]</i>
AO	<i>[Signature]</i>
	<i>[Signature]</i>
	<i>[Signature]</i>

1. Enclosures (1) and (2) detail currently used procedures and standards for analysis of underwater sound pressure levels associated with diver tools being evaluated for use by Navy divers. As noted in reference (a), concerns raised about procedures, standards and analyses currently in use significantly complicate NAVSEA responsibility in evaluating and authorizing for Navy use essential underwater tools for Navy divers. The need exists to establish a unique underwater standard for diver-safe sound pressure limits; however, NAVSEA concurs in the apparent reasonableness and safety of procedures and analyses currently in use and outlined in enclosure (1). Recognizing the difficulty and time involved in establishing a permanent standard, it is requested that BUMED review currently used procedures and standards (enclosures 1 and 2) with the intent of providing interim guidance for use in evaluating diver used underwater tools. Subsequent establishment of an approved standard for underwater sound pressure limits should be undertaken as an active project.

[Signature]
R. P. SAMPSON
For Direction

Copy to:
BUMED
BUMED (Code 314)
NCSC
NCSC (Code 715)
NEDU
NMRDC (Code 41)
NSMRL
NCEL

NAVY ENVIRONMENTAL HEALTH CENTER
NAVAL STATION
NORFOLK, VIRGINIA 23511

33:JWG:naf
6293.1
Ser 06158
17 Jun 1982

From: Commanding Officer, Navy Environmental Health Center
To: Chief, Bureau of Medicine and Surgery (MED 03)

Subj: Underwater Sound Pressure Level Limits

Ref: (a) CHBUMED ltr BUMED-3C21:NAD:meb 6240 dtd 15 Apr 1982
(b) CO NAVXDIVINGU ltr NEDU:RAB:cz 6420 Ser 90 dtd 19 Mar 1982

Encl: (1) Draft Letter

1. As requested in reference (a), the Navy Environmental Health Center (NAVENVIRHLTHCEN) has reviewed the enclosures to reference (b). Enclosure (1) is the draft letter for Chief, Bureau of Medicine and Surgery for interim guidance on subject problem.
2. NAVENVIRHLTHCEN will coordinate the development of a proposed BUMED instruction on underwater sound pressure level limits.
3. Point of contact on this subject is Mr. J.W. Greene, Head, Hearing Conservation Branch, AUTOVON: 690-4657, Commercial: (804) 444-4657.

R.A. Nelson
R.A. NELSON

CO	
AO	



DEPARTMENT OF THE NAVY
BUREAU OF MEDICINE AND SURGERY
WASHINGTON, D.C. 20372

IN REPLY REFER TO
BUMED-3C21:NAD:sib
6420

5 July 1982

From: Chief, Bureau of Medicine and Surgery
To: Commander, Naval Sea Systems Command (SEA-00C)

Subj: Underwater Sound Pressure Level Limits

Ref: (a) CO NAVXDIVINGU 1tr NEDU:RAB:cz 6420 Ser 90 dtd 18 MAR 82
(b) DODINST 6055.3
(c) OPNAVINST 6260.2

1. The Navy Environmental Health Center (NAVENVIRHLTHCEN), acting as the Bureau of Medicine and Surgery (BUMED) Hearing Conservation Program Manager, has reviewed the enclosures to reference (a) and finds the guidelines in use at the Navy Experimental Diving Unit are too lenient. Many of the assumptions underlying the guidelines are open to question and are not adequately supported by research in underwater hearing.

2. NAVENVIRHLTHCEN finds the 26 decibels (dB) correction for the change in reference level is correct. However, the adjustments for the acoustic impedance mismatch and the A-weighting factor used in airborne noise criteria may be in error. Further, references (b) and (c) require a more stringent criterion for damage risk than proposed by Occupational Safety and Health Administration (OSHA) recommendations. The DOD and OPNAV criteria are based on S4 dBA for 8 hours with a 4dB trading relationship.

3. The Chief, BUMED is undertaking the development of a comprehensive BUMED instruction on underwater noise limits. In the interim, the following guidelines are provided:

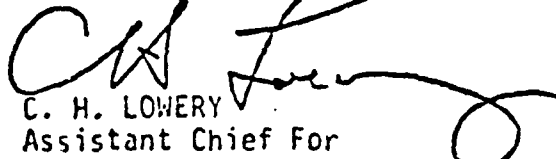
- a. Continue to use standard techniques and instrumentation developed by the underwater sound community and to thoroughly document each test and evaluation of underwater tools and equipment.
- b. Recompute the correction factor for impedance mismatch deleting the A-weighting factor. Perform the following steps for each test:
 - (1) Obtain octave band levels of noise spectrum from 125 to 8000 hertz (Hz).
 - (2) Subtract underwater hearing threshold levels at each octave frequency.
 - (3) ~~Subtract~~ ^{Add} minimum audible field values for threshold in air.
 - (4) Use ~~minimal~~ ^{overall 5 ft contour} octave band level to compute allowable exposure time.
- c. Use the 900 criterion of 11 dB for 8 hour periods with the 4 dB trading relationship for computing allowable exposure time.

ENCLOSURE 2

BUHED-3C21:RAD:slb
6420
6 July 1982

Subj: Underwater Sound Pressure Level Limits

- d. Add equivalent noise dose in water to noise dose in air to obtain total daily noise dose for exposed personnel.
- e. Do not use correction factors for attenuation of noise by wet suit hood or the ear canal filled with water.
- f. For noise with the preponderance of energy outside the frequency range of 125 to 8000 Hz or for impulse noise consult with Auditory Research Department, Naval Submarine Medical Research Laboratory, New London, Connecticut.
- g. Conduct annual monitoring hearing tests on exposed personnel, with follow-up and disposition in accordance with reference (c).


C. H. LOWERY
Assistant Chief For
Health Care Programs

Copy to:
CO, NAVMEDRSCHDEVCOM Bethesda MD (Code 47)
CO, NAVSUBMEDRSCHLAB, New London CT
CO, NAVXDIVINGU, Panama City, FL
CO, NAVCOASTSYSCEN, Panama City, FL
CO, NAVENVIRHLTHCEN ←

Memorandum

TO : Lt. D. Styer, Navy Experimental
Diving Unit

DATE: 30 July 1982

FROM : P. Smith, Naval Submarine Medical Research Laboratory

SUBJECT: Underwater Sound Pressure Level Limits

- Ref: (a) BUMED - 3C21:NAD:slb 6420 (no serial) dtd 5 July 1982
- (b) COMNAVSEASYSKOM ltr OOC/SAD 5100 Ser 461 dtd 12 Apr 1982
- (c) Brandt, J.F. and H. Hollien. Underwater Hearing Thresholds in Man, J. Acoust. Soc. Amer. 42, pp 966-971, 1967.
- (d) International Organization of Standardization, Geneva, Switzerland, "Normal equal-loudness contours for pure tones and normal threshold of hearing under free-field listening conditions". ISO standard R 226-1961.
- (e) OPNAVINST 6260.2

Encl: (1) Worked out example for determining permissible times for exposure to noise in water.

1. The interim guidance on subject matter provided by ref (a) should be applied as in the worked out example in enclosure (1). Proceed as follows:

line 1: The center frequencies of the Octave Band Levels (OBLs) to be used. OBLs may be computed from three corresponding 1/3 Octave Band Levels.

line 2: OBLs in dB re 20 micropascals (μPa). The values used in this example are taken from Fig. 1 of encl (2) to ref (b) for the NCSC Test Pool data of 5-6 Mar 1980. (Levels 20-30 dB below peak level will not contribute significantly to the result. Hence, the uncertain but relatively low level for the 8000 Hz Band has been arbitrarily assigned a value of 0dB).

line 3: Underwater hearing threshold levels taken from ref (c).

line 4: Subtract line 3 from line 2 to obtain "Band Sensation levels".

line 5: Minimum Audible Field threshold levels in air from ref (d).

line 6: Add line 4 to line 5 to obtain OBLs for an equivalent exposure in air. Note that par 3.b. (3) of ref (a) erroneously states that the air thresholds should be subtracted.

line 7: Compute an overall exposure level using the formula

$$L_{\text{OBL}} = 10 \log_{10} \left(\sum 10^{L_i/10} \right)$$

where L_i are the OELs from line 6. Taking the single highest OEL as recommended in ref (a) (par 3.b. (4)) would underestimate exposure levels by almost 3dB in this example.
line 8: Compute permissible exposure time using the formula

$$T = 16 \div 2^{\left(\frac{L-82}{4}\right)}$$

where L is the L_{COMB} computed in line 7. This formula is given in ref (a).

2. If you have further questions please call.

Paul

Worked out example for determining permissible times for exposure to noise in water

[illegible]

NEDU:WAE:prs

6420

Ser

293

25 AUG 1982

CO	
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CB	ONE

Copied to T. H. Smith
FO

From: Commanding Officer, Navy Experimental Diving Unit
To: Commander, Naval Sea Systems Command (OOC-22)
Commanding Officer, Naval Environmental Health Center
Commanding Officer, Naval Submarine Medical Research Laboratory
Commanding Officer, Naval Coastal Systems Center (Code 2210)
Commanding Officer, Naval Medical Research and Development Command
(Code 47)
Chief, Bureau of Medicine and Surgery
Commanding Officer, Naval Civil Engineering Laboratory

Subj: Diver Tool Sound Pressure Level Limits

Ref: (a) BUMED ltr 3C21 6420 dtd 15 APR 82
(b) BUMED ltr 3C21 6420 dtd 5 JUL 82

1. Reference (a) initiated a review of the overall underwater noise hazard problem, drafting of definitive guidance on underwater sound pressure level (SPL) limits and provided interim guidance for Naval Sea Systems Command (NAVSEA) in granting Authorized for Navy Use (ANU) to diver tools. In pursuit of these goals with respect to diver tools you are invited to attend a one day conference at the Navy Experimental Diving Unit (NEDU), Panama City, FL on Tuesday, 14 September 1982 to initiate the proposed two year project. Diver tool underwater SPL data collection methodology and Bureau of Medicine and Surgery (BUMED) interim guidance reference (b) will be the major topics of discussion.


R. A. BORNHOLDT



DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407

IN REPLY REFER TO:

NEDU:WAE:cz
6420

Ser

404
29 OCT 1982

From: Commanding Officer, Navy Experimental Diving Unit
To: Commander, Naval Sea Systems Command (SEA-00C)

Subj: Diver Tool Noise Conference Summary

Ref: (a) BUMED-3C21 ltr 6420 dtd 5 JUL 82
(b) NAVSEAINST 9597.1 CH-4 dtd 18 MAR 76

Encl: (1) List of Attendees

1. A Diver Tool Noise Conference was held at the Navy Experimental Diving Unit (NEDU) on 14 September 1982 to discuss in detail the provisions of reference (a), Bureau of Medicine and Surgery (BUMED) interim guidance on underwater noise limits. The conference attendees, enclosure (1), agreed upon the following revised detailed steps for computing the permissible times for exposure to noise underwater:

a. Measure the sound pressure level in the octave bands with the following central frequencies: 125, 250, 500, 1000, 2000, 4000, 8000 hz, using standard techniques and instrumentation developed by the underwater sound community.

b. Convert each octave's sound pressure level to a reference level of 20 micro pascals (.000204 dynes/cm²). If the measurements were taken with a reference level of 1 micro pascal, it is necessary to subtract 26 dB to convert to the 20 micro pascal reference level.

c. From each octave band's sound pressure level, subtract the underwater hearing threshold levels for that octave band as follows:

125 hz - 70 dB	2000 hz - 66 dB
250 hz - 65 dB	4000 hz - 67 dB
500 hz - 58 dB	8000 hz - 74 dB
1000 hz - 60 dB	

d. To the result from step 3, add the minimum audible field values for threshold in air at each octave band as follows:

125 hz - 21 dB	2000 hz - 1 dB
250 hz - 11 dB	4000 hz - -3 dB
500 hz - 6 dB	8000 hz - 10 dB
1000 hz - 4 dB	

Subj: Diver Tool Noise Conference Summary

e. From the results from step 4, calculate the overall sound pressure level of the tool by summing all of the sound pressure levels for each of the octave bands; i.e., 125, 250, 500, 1000, 2000, 4000, 8000 hz, as follows:

$$L_{comb} = 10 \log_{10} (\sum 10^{L_i/10})$$

where

L_i = the sound pressure level in a given octave band

L_{comb} = the combined or overall sound pressure level of the tool.

f. Calculate the permissible exposure time using the DoD criterion of 84 dBA for 8-hour periods with the 4 dB trading relationship.

$$\text{Time} = \frac{16}{2} \frac{(L_{comb}-80)}{4}$$

2. The interim guidance provided in reference (a) does not include underwater noise exposure limits for a diver wearing a dry helmet. Diver tools are presently being used with dry helmets. Therefore, the Naval Sea Systems Command (NAVSEA OOC) representative agreed to request interim guidance from BUMED for the dry helmeted diver exposed to underwater noise.

3. Mr. Wyman of NCSC, Diving, Salvage and Ship Husbandry Branch, agreed to provide Navy Submarine Medical Research Lab (NSMRL) with test reports on diver tool underwater sound pressure levels to assist NSMRL's effort of providing definitive standards on underwater tool noise.

4. NAVSEA OOC representative agreed to request BUMED approval of the conference's revised interim guidance, paragraph 1. Upon receipt of BUMED approval, diver exposure times identified in reference (b) should be recalculated by NCSC.


FRANK E. EISSING

Copy to:

NCSC (Code 2210)

NAKDC (Code 41)

NCEL

NSMRL

NAWVIRNLTTCEN

BUMED (Code 3021)

LIST OF ATTENDEES

<u>NAME</u>	<u>ORGANIZATION</u>	<u>AUTOVON PHONE NUMBER</u>
CDR F. E. EISSING	NEDU	436-4351
CDR R. J. BIERSSHER, MSC	NMRDC/NNMC	295-1525
LCDR W. A. EVANS	NEDU	436-4351
LT D. STYER	NEDU	436-4351
MR. E. W. GLAUBITZ	NAVSEA OOC	227-7403
MR. F. GOULD	NCSC	436-4386
MR. J. W. GREENE	NAVENVIRHLTHCEN	690-4657
MR. J. E. JORDAN	NSMRL	241-4907
MR. J. MITTLEMAN	NCSC	436-4388
MR. J. QUIRK	NCSC	436-4388
MR. P. F. SMITH	NSMRL	241-3201
MR. K. TATE	NCEL	360-5794
MR. D. WYMAN	NCSC	435-4388



DEPARTMENT OF THE NAVY

NAVAL SEA SYSTEMS COMMAND

WASHINGTON, DC 20362

IN REPLY REFER

OOC/EWG

Ser 1813

10 Nov 198


From: Commander, Naval Sea Systems Command
To: Chief, Bureau of Medicine and Surgery (Code 3C21)

Subj: Underwater Sound Pressure Level Limits

Ref: (a) BUMED-3C21 ltr 6420 of 5 Jul 1982

Encl: (1) NEDU ltr ser 404 of 29 Oct 1982

1. Reference (a) provided interim guidance for the interpretation and use of underwater sound pressure data for determining acceptable exposure times for divers.
2. Enclosure (1) summarizes a conference held on 14 September 1982 at the Navy Experimental Diving Unit concerning the application and revision of reference (a).
3. It is requested that BUMED review the detailed steps for computing the acceptable times for exposure to underwater noise as presented in enclosure (1). Upon receipt of concurrence by BUMED, acceptable diver exposure times to underwater sound produced by diver tools will be calculated.
4. Reference (a) does not appear to provide guidance for exposure to underwater sound by dry helmeted divers. It is requested that BUMED provide interim guidance for the dry helmeted diver.
5. NAVSEA point of contact is Mr. Eric Glaubitz, telephone (202) 697-7403.


R. P. SWANSON
By Direction



DEPARTMENT OF THE NAVY
BUREAU OF MEDICINE AND SURGERY
WASHINGTON, D.C. 20372

20 077
IN REPLY REFER TO
BUMED-3C21:NAD:slb
6420
27 December 1982

From: Chief, Bureau of Medicine and Surgery
To: Commander, Naval Sea Systems Command, (SEA-00C)


Subj: Underwater Sound Pressure Level Limits

Ref: (a) BUMED-3C21:NAD:slb ltr 6420 of 5 JUL 82
(b) OPNAVINST 6260.2

Encl: (1) NAVSEA OOC/EWG ltr Ser 1813 of 10 NOV 82
(2) NEDU:WAE:ca ltr 6420, Ser 404 of 29 OCT 82

1. In accordance with enclosure (1), enclosure (2) has been reviewed. BUMED concurs with the revised detailed steps for computing the permissible times for exposure to noise underwater. Enclosure (2) should be used where conflict exists with the guidance provided in reference (a).

2. For the dry helmeted diver specific guidance is considered inappropriate. The standards for airborne noise promulgated by reference (b) apply within the airspace of the helmet, as measured therein. To ensure accurate measurement the measuring microphone must be calibrated to the ambient pressure using the electrostatic actuator.


R. L. MARLOR
Assistant Chief for
Health Care Programs
Acting

Copy (with encls) to:

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CO, NAVXDIVINGU, Panama City, FL
CO, NAVCOASTSYSCEN, Panama City, FL
CO, NAVENVIRHLTHCEN, Norfolk, BA (Code 33)
CO, NAVCIVENGRLAB, Port Hueneme, CA

07 JAN 1983



PANAMA CITY, FLORIDA 32407

IN REPLY REFER TO:

NEDU:WAE:CZ

5100

Ser 4?

15 FEB 1983

From: Commanding Officer, Navy Experimental Diving Unit
To: Commander, Naval Sea Systems Command (SEA-OOC)

Subj: Allowable Sound Pressure Levels (SPL) Inside Diving Helmets

Ref: (a) NAVSEA ltr OOC/WRB 5100 Ser 017 dtd 5 JAN 83
(b) BUMED ltr 3C21:NAD 6420 dtd 27 DEC 82
(c) BUMED ltr 3C21:NAD 6420 dtd 15 APR 82

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1. In response to reference (a), NEDU's review of OPNAVINST 6260.2 and NAVSEAINST 6260.1 concludes that both instructions are applicable in regard to establishing noise control standards for diving helmets. This is additionally confirmed by reference (b). It should be noted that at the present time the allowable sound pressure limits remain constant regardless of diver depth.

2. Bureau of Medicine and Surgery (BUMED) tasked the Navy Environmental Health Center (NAVENVHLTHCEN) by reference (c) to develop a proposed BUMED instruction to serve as definitive guidance on underwater sound pressure level (SPL) limits. It is recommended that NAVSEA identify to BUMED the requirement to include hyperbaric SPL limits as well.

3. While the NAVENVHLTHCEN may provide more definitive guidance on hyperbaric SPLs over the long run, the problem of MK 14 Mod 1 SPLs must be addressed in the short term. The current guidance of not allowing SPL limits to change with increasing gas density has not been substantiated by manned data as far as we have been able to determine. To this end it is recommended that NEDU be tasked to do a series of manned studies on the MK 14 Mod 1 to depths of 650 FSW to determine if its SPLs may be harmful for the required 4-hour mission exposure. NEDU would consult with appropriate individuals in the Navy medical community [e.g. J. W. Greene, NAVENVHLTHCEN and P. F. Smith, NAVSUBMEDRSHLAB] in devising testing procedures and analyzing results. This data along with projected individual diver career exposure to the MK 14 Mod 1 would then be used as a basis for requesting a waiver of the airborne SPL limits for the MK 14 Mod 1. As a spinoff, this study would also provide useful data for any long term studies undertaken by NAVENVHLTHCEN. It should be emphasized that this tasking would be for solution of a single short term problem and would complement rather than supplant any long term programs for investigating hyperbaric SPLs.

Frank E. Eissing
FRANK E. EISSING

Copy to:

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CO, NAVENVHLTHCEN, Norfolk, VA (Code 33)
CO, NAVMEDRSCHDEVCOM, Bethesda, MD (Code 47)

18 FEB 1983

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

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19 ABSTRACT (Continue on reverse if necessary and identify by block number) A critical review of past research conducted on underwater hearing, particularly on underwater thresholds of audibility, has revealed that current underwater noise exposure limits may be too lax. Further new experimental work at suprathreshold sound levels also supports the need to lower current underwater permissible noise exposure values. A new approach to establishing an underwater noise exposure standard is proposed. Information is provided on the hearing protection provided by divers' hoods. Some tutorial information is also provided on the anatomy and functioning of the ear, on sound level reference values, and on the means to convert in-air audiometric data to equivalent in-air sound field data for comparison with underwater sound field data.					
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Block 18 continued:

underwater acoustic reflex thresholds; equal loudness comparison (air vs water); sound level reference values; Minimum Audible Field (MAF); Minimum Audible Pressure (MAP); Minimum Audible Pressure as Measured by a Standard Coupler (MAPC); audiometric standards; Temporary Threshold Shifts (TTS); spectral weighting underwater; permissible exposure levels underwater. ~~See~~ ~~2~~